AUTOMATION, ANNUNCIATION, AND EMERGENCY SAFETY SHUTDOWN OF A LABORATORY MICROGRID USING A REAL-TIME AUTOMATION CONTROLLER (RTAC)

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Dedicated to my father and mother
whose endless love and support carry me through difficult times.

ABSTRACT

Automation, Annunciation, and Emergency Safety Shutdown of a Laboratory Microgrid using a Real-time Automation Controller (RTAC)

Do Vo

Over the last decade, microgrid deployments throughout the world have increased. In 2019, a record number of 546 microgrids were installed in the United States [1]. This trend continues upward to combat extreme weather conditions and power shortages throughout the country. To better equip students with the necessary skillsets and knowledge to advance in the microgrid field, Cal Poly San Luis Obispo's Electrical Engineering Department and the Power Energy Institute have invested resources to develop a laboratory microgrid.

This thesis sets to improve the laboratory microgrid's existing automation using the Schweitzer Engineering Laboratory SEL-3530 Real-time Automation Controller (RTAC). The improved automation features a new load-shedding scheme, LCD annunciator and meter panel, and emergency safety shutdown system. The load shedding scheme aims to enhance the grid's frequency stability when the inverter-based power output declines. The LCD annunciator and meter panels provide real-time oversight of the microgrid operating conditions via the RTAC Human Machine Interface (HMI). The emergency safety shutdown enables prompt de-energization and complete isolation of the laboratory microgrid in hazardous conditions such as earthquake, fire, arcing, and equipment malfunction and activates an audible siren to alert help. This safety system provides safety and peace of mind for students and faculties who operate the Microgrid. Lastly, this thesis provides an operating procedure for ease of operation and experiment.

Keywords: SEL-3530 RTAC, microgrid, safety shutdown, annunciation, three phase power, protection.

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The Microgrid is a cooperative project that has been built by many generations of Cal Poly electrical engineering students. The following individuals deserve utmost credits in developing the Microgrid: Virginia Yan, Eric Osborn, Matthew Guevara, Kenan Pretzer, Nathan Martinez, Garvin Yee, Yei Trinh, Nicole Rexwinkel, and Joshua Cinco. Many thanks to Schweitzer Engineering Laboratories Inc. for the generous equipment donation.

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1.1 TRADITIONAL GRID

The typical traditional grid consists of generation units, step-up transformers, transmission lines, step-down (distribution) transformers, and loads. The generators are located far from the load and rely on step-up transformers and transmission lines to deliver power over a long distance. The voltage needs to be stepped down by a distribution transformer to feed the loads (Figure 1). The U.S. electric grid consists of three interties (Figure 2) with 300 electric utilities and over 300,000 miles of transmission and distribution lines. In the traditional grid, power flows unidirectionally from power plants to the load, referred to as non-distributed generation [2].

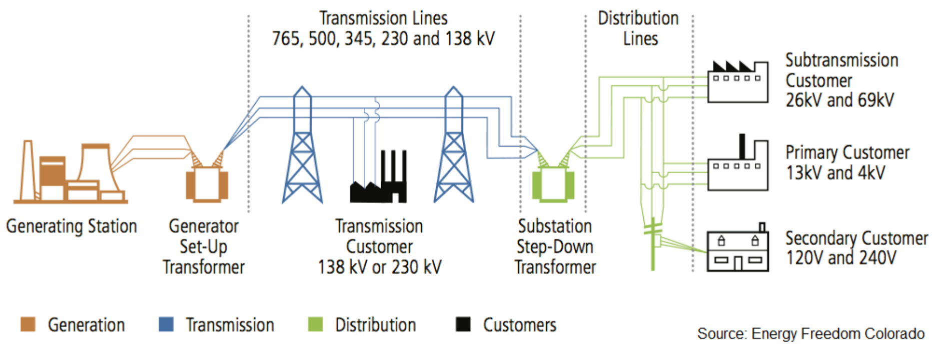


Figure 1. Electric Grid Infrastructure

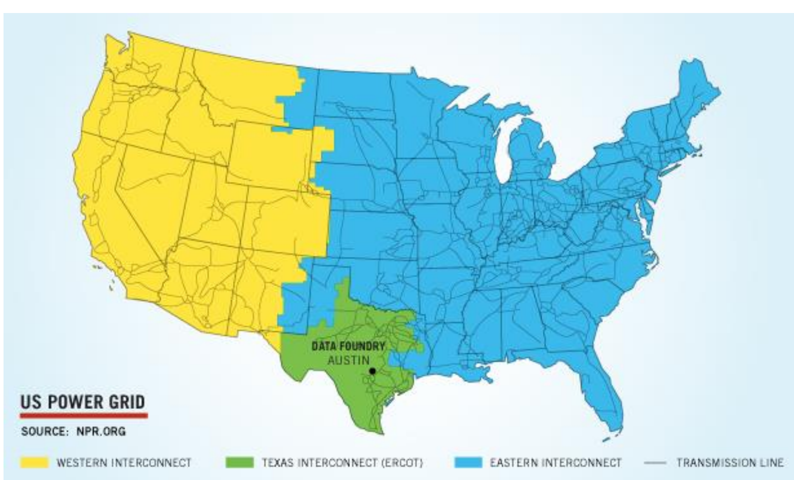


Figure 2. The United States Electrical Grid

1.2 THE SMART GRID

The smart grid shares a similar distribution and transmission infrastructure with the traditional grid. However, much like the Internet, the smart grid incorporates modern technology such as automation, control, computer, and smart meter, enabling bidirectional communication between the utility and the customer and remote assets. The smart grid better represents the modern-day grid which replaces the traditional grid by moving generating units closer to the load with sophisticated levels of automation and communication (Figure 3). In a smart grid system, renewable resources such as solar turn the power flow into a bidirectional flow. All grid-tied electrical equipment and protection relays communicate to increase efficiency and reliability [2].

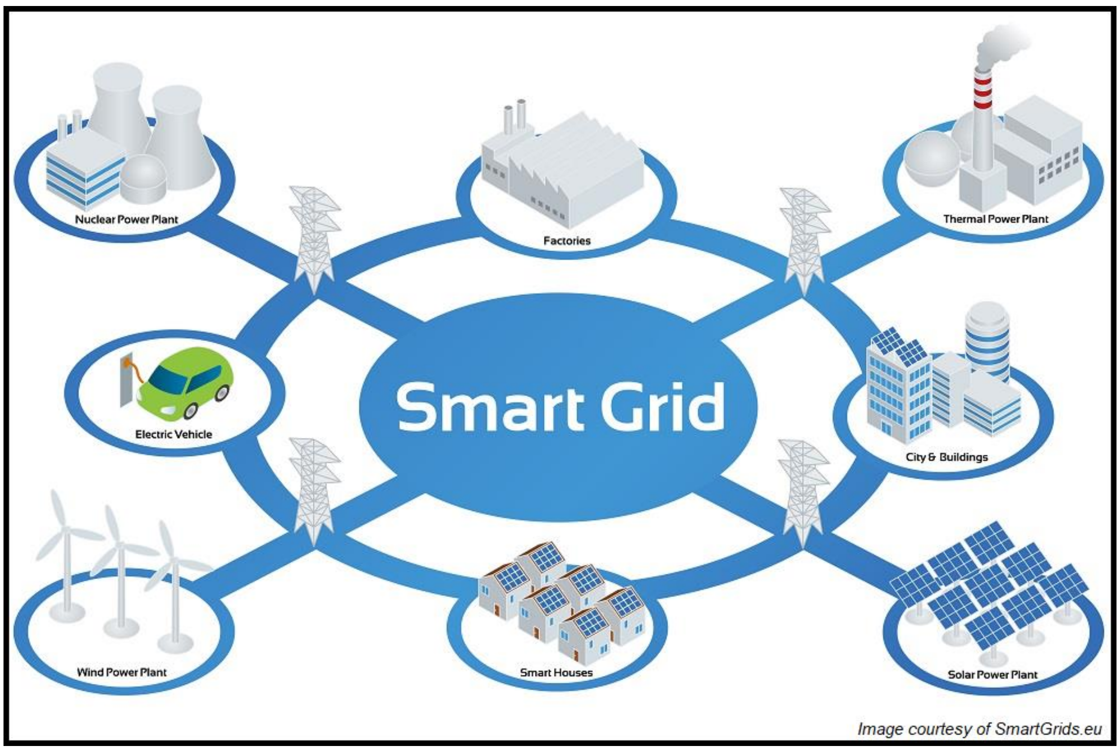


Figure 3. Smart Grid depiction

1.3 THE MICROGRID

The microgrid shares many characteristics with the smart grid, such as automation, communication, and intelligent protection systems. What sets the microgrid apart is the ability to be independent, intelligent, and local. The microgrid can island (isolated from the utility grid) and self-sustain for a designed period. In a microgrid system, the loads are much closer to the generating units.

The Cal Poly Microgrid (referred to throughout this paper as “the Microgrid”) is a laboratory electrical system that closely replicates a practical microgrid seen throughout the industry. The Microgrid is self-sustained with a pair of synchronous generators and renewable energy generation via solar panels and microinverter. The resistive load and induction motor were incorporated to represent residential and agricultural load. The Microgrid is protected and automated by Schweitzer Engineering Laboratories (SEL) relays capable of tripping or closing the circuit breakers (Figure 4).

Figure 4. Cal Poly Microgrid

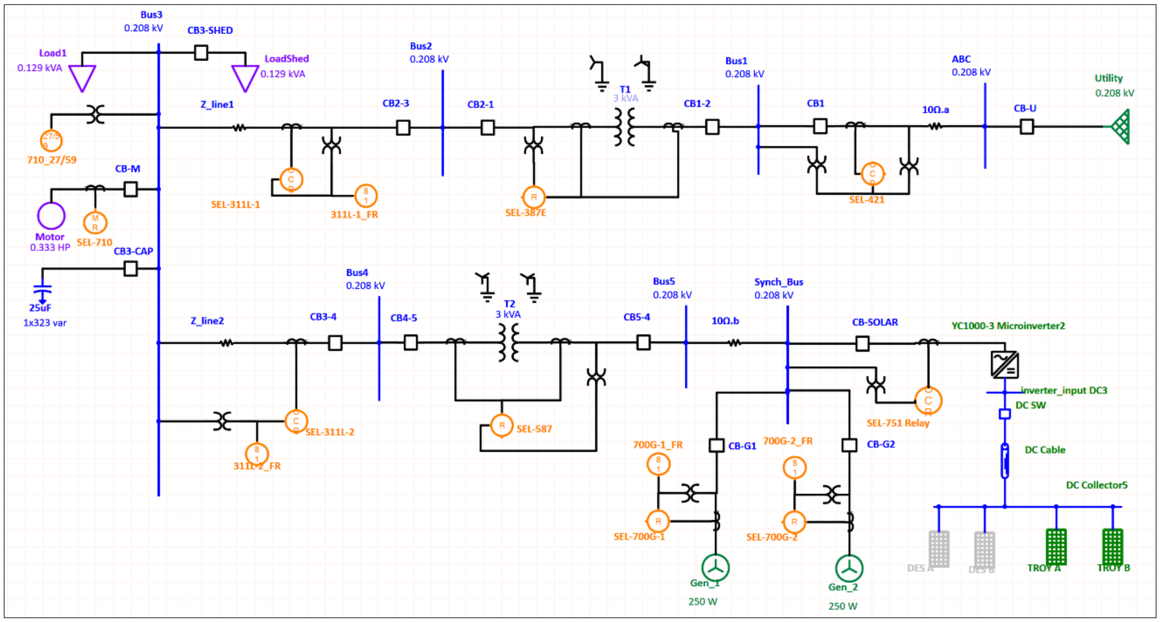


Figure 5. Cal Poly Microgrid Single Line Diagram (ETAP Software)

1.4 MICROGRID RENEWABLE ENERGY INTEGRATION [4]

The Microgrid Renewable Energy Integration was a senior project completed by an electrical engineering student, Do Vo. The project integrated the Grid-Tied Solar System [5] into the Microgrid and provided a series of tests and solutions to ensure the microinverter can remain operational during the isolation process between the Microgrid and the infinite bus (building grid). In addition, the SEL-751 Feeder Protection Relay, SEL-735 Power Quality, and circuit breaker were installed to provide primary protection function to the renewable energy branch.

CHAPTER 2. BACKGROUND

The Microgrid has evolved over the years to incorporate many features that enable the system to replicate a practical microgrid closely. Such development includes introducing the twin synchronous generators to supply power, the solar panels and microinverter to deliver renewable energy, an induction motor to mimic agriculture load, and the intelligent state-of-the-art Schweitzer Engineering Laboratories (SEL) protective relays to protect the system. This laboratory electrical system offers meaningful opportunities for electrical engineering students at Cal Poly to safely study the behaviors and characteristics of a microgrid. As the Microgrid continues to expand its capability, many shortfalls began to manifest and require improvement. For example, renewable energy generation's introduction transformed the Microgrid from a static to a dynamic system. Power fluctuation from the panels due to shading can significantly impact the grid frequency, thus stability. Equipment such as the generators, DC starters, SEL relays, circuit breakers, microinverter, and cables started to overcrowd lab benches #5 and #6 where the Microgrid stations. Safety features used to safely de-energize the lab became physically challenging to access, potentially leading to safety hazards at the work area.

Furthermore, the addition of more equipment inevitably led to an overwhelming number of parameters to maintain, such as generator voltage, generator frequency, breaker status, microinverter status, load status, relay trip setpoints. The operation of the Microgrid became inefficient and often inconvenient. Improvements are urgently needed to ensure the Microgrid can be safely studied and experimented with by the curious mind.

CHAPTER 3. DESIGN REQUIREMENTS

This project consists of three engineering designs: automation, annunciation, and emergency safety shutdown system. Each design category strictly follows the corresponding requirements and specifications outlined. An operating procedure, see Appendix B, will be used to test the overall performance of the designs.

Table 1. Automation Design Requirements and Specifications

Design Requirements	Engineering Specifications	Justification
1	All SEL relays communicate bidirectionally with the SEL-3530 RTAC to adapt to various grid conditions and maintain grid situational awareness.	Communication between the RTAC and the SEL relays enables data exchange, thus allowing automated and informed corrective action to be taken by RTAC and the relays.
2	The SEL-3530 RTAC and SEL-311L will shed load when power deficiency is detected.	The Microgrid's synchronous generator's manual operation cannot adjust output power following an abrupt decrease in solar panels' power output. The RTAC and the SEL-311L can load shed to stabilize the Microgrid.
3	The SEL-751 changes group setting when commanded by the Rigol signal via SEL-3530 RTAC and SEL-2505 Remote I/O Module.	Each group setting of the SEL-751 consists of the same set of protection elements at various setpoints to protect during different grid conditions. This feature demonstrates a proof of concept to remotely change an SEL relay from a non-SEL device for use in the future wildfire risk reduction projects.
4	Grid parameters are gathered and processed by the SEL-3530 RTAC.	Grid data gathering enables the RTAC to generate informed corrective action such as load shedding and display grid status on the annunciator panel.
5	Safely and quickly de-energize the Microgrid due	Overcrowded equipment prevents quick access to the safety switches at

<table>
<tr><td></td><td>to unsafe operating conditions.</td><td>lab benches #5 and #6 and at the distribution panel—prompt de-energization of the Microgrid to ensure students and faculty safety.</td></tr>
<tr><td colspan="3">Marketing Requirement
1. SEL relays bidirectionally communicate with SEL-3530 Real-Time Automation Controller (RTAC)
2. Load-shed during low solar panel power output
3. Change group settings
4. Grid situational awareness
5. Safe shut down of the Microgrid</td></tr>
</table>

Table 2. Annunciation Design Requirements and Specifications

Design Requirements	Engineering Specifications	Justification
1	The annunciator panel displays accurate alarms that closely reflect the grid condition and event.	The operator relies on accurate information to make informed decision and respond appropriately to various grid condition. Accurate annunciation enhances grid situational awareness.
2	The LCD display of each alarm must be readable from 10 feet away.	The generator #1 cart is approximately 10 feet away from the LCD screen. Each alarm display must be large enough for the operator to recognize. Large display can reduce reading error and misunderstanding.
3	Alarm title must be concise and easy to understand.	Concise alarm title ensures the operator can quickly understand the meaning of each and take appropriate corrective action.
4	The annunciator panel reports the alarm with minimal delay.	Time can be of essence when certain unfavorable grid condition occurs. Delayed alarm can hinder the operator's ability to make timely decision.
5	The annunciator shall be expandable to incorporate new alarms for future Microgrid expansion.	Future devices such as weather station, wind turbine, and automatic voltage regulator necessitate designated alarms.
6	Key grid values such as power, frequency, voltage from the generating units shall be displayed.	Generator frequency, voltage, and power reading are critical to the synchronization process and help the operator stabilize the plant condition following a disturbance.
Marketing Requirement 1. Provide accurate alarm 2. Visually observable from up to 10 feet away 3. Easy to understand 4. Prompt display 5. Expandability 6. Power meter		

Table 3. Emergency Safety Shutdown System Design Requirements and Specifications

Design Requirements	Engineering Specifications	Justification
1	Immediately shutdown the Microgrid in a safe manner	Immediate de-energization of the Microgrid ensures any electrical hazardous condition is quickly suppressed. Prompt shutdown can reduce arch flash energy or deescalate any voltage or current induced faults.
2	Completely isolate the Microgrid from any source of energy.	Complete isolation ensures no back feeding and unaware live components. Complete isolation enhances the overall safety of the Microgrid.
3	Redundant ESS switches and tripped breaker.	Redundant ESS switches located at three sides of the Microgrid where the operator stations to run the system ensures constant accessibility. Redundant tripped breakers ensure complete isolation in case the primary breaker fails to trip.
4	The siren will go off when ESS switch is actuated.	The siren draws great attention and alert nearby students of an emergency. The potentially injured operator has a higher chance of getting help.
5	The ESS system must be easy to activate.	Easy of operation ensures the ESS system can be activated when necessary with minimal effort.
Marketing Requirement 1. Safely and quickly deenergize the Microgrid 2. Complete isolation 3. Redundancy 4. Activate the siren 5. Easy to operate		

CHAPTER 4. AUTOMATION

Automation plays an essential role in setting the microgrid apart from the traditional grid by enabling communication and control between microprocessor relays within the network, thus, allowing informed decision-making processing. The microgrid automation allows faster corrective action and coordination that would otherwise require timely human intervention. The Microgrid described throughout this paper features such automation capability to ensure the ability to operate in two configurations: grid-tied and islanded. These configurations necessitate the automation of many operations of Microgrid to provide reliable and consistent power [6].

4.1 INDUSTRY OPERATING EXPERIENCE [13]

On April 19, 1996, Southwestern Public Service Company, a subsidiary of Xcel Energy, experienced a major system disturbance. The washing of 230 kV breaker TK47 caused an adjacent bushing to arc to the ground resulting in a differential relay trip. Additional breakers opened to clear a single “C” phase-to-ground fault on breaker TK47, causing Tolk unit No. 1 and No. 2 turbines out of service. This loss led to more than 1000 MW deficiency on the grid. A 230 kV bus backup relay (Zone 3) at Plant X saw the fault and operated. The relay timer failed to drop out after the fault was cleared, causing a miscoordination that triped all breakers on the 230 kV bus at Plant X. This miscoordination removed Plant X unit No. 4 and two major transmission ties out of service. The voltage across the system began decreasing. The 345kV Tuco – Oklaunion tie, 23 kV Tuco – Swisher County line, 230 kV Nicholls – Elk City tie, and 115 kV Nichols – Shamrock subsequently opened by system protection. Frequency rapidly dropped. Underfrequency relays within the Special Protection Scheme (SPS) operated to shed 700 MW load. The system slowly stabilized after the grid operator incrementally restored the transmission lines and generating units.

Investigations identified several problems, including protection, prevention, and restoration. The existing load shedding has three steps of underfrequency relays that operate at 59.3 Hz, 59.0 Hz, and 58.7 Hz and shed about 10% of the demand in each step. On April 15, only 700 MW was shed, which could not compensate for the 1000+ MW deficiency. The North American Electric Reliability Corporation (NERC) recommended adding additional automatic load shedding. The recommended scheme added a fourth step of under frequency relays set at 58.4 Hz.

4.2 REAL-TIME AUTOMATION CONTROLLER (RTAC)

Schweitzer Engineering Laboratories SEL-3530 RTAC is a multifunctional controller and data concentrator. The RTAC offers various data types, communication protocols, logic programs, and tag lists that can be used to monitor, control, and automate the electrical system. In the Microgrid, the RTAC collects real-time data from the SEL relays such as SEL-751, SEL-710, SEL-700G, SEL-421, and multiple DC/AC control input signals. Gathered and processed data can be used to monitor the Microgrid's operation, annunciate abnormal states, and automate breaker tripping and closing.

Figure 6. SEL-3530 Real-Time Automation Controller (Front)

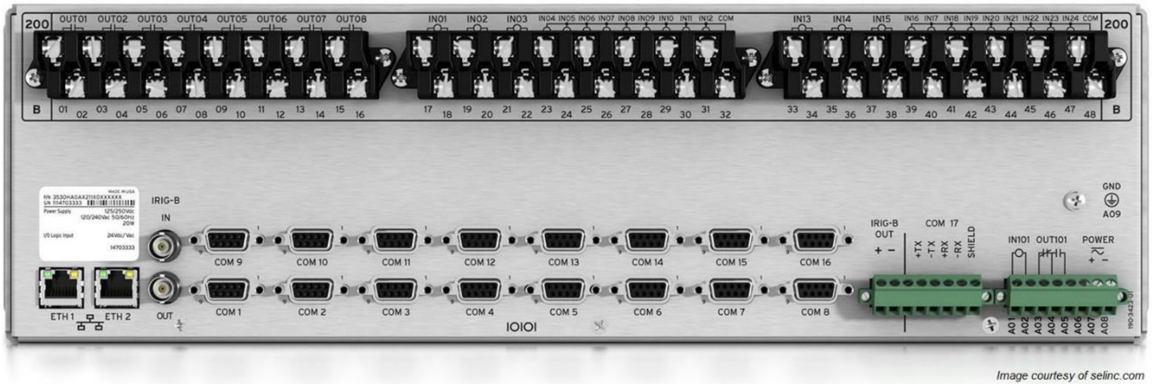


Figure 7. SEL-3530 Real-Time Automation Controller (Back)

4.3 EXISTING MICROGRID AUTOMATION [6]

The successful operation of the Microgrid thus far relies on the following automated tasks: power factor correction, load shedding, relay group switching, utility synchronization, and generator synchronization. Power factor correction is achieved using the SEL-710 Motor Protection Relay that automatically connects the capacitor banks to the induction motor’s terminals. The SEL-710 under/over voltage element automates the capacitor bank switching as the bus voltage falls below 174V line-to-line and drops the capacitor bank when the voltage rises above 214V line-to-line. When the Microgrid transfers to the islanded mode, grid stability requires automatic load shedding as the generators must pick up any power the utility provides. Sudden electrical load pick-up will cause the generator frequency to dip below 60Hz; thus, initial load shedding must be implemented to maintain the desired system frequency at 60Hz. To accomplish load shedding, the RTAC monitors real-time frequency data from the SEL-700G Generator Protection Relay. If the SEL-700G detects a frequency below 59.67Hz (1790RPM), the RTAC will send a trip signal to the SEL-311L to trip the breaker connecting the 333-Ohm static load (red arrows in Figure 8). This load shedding only operates when islanding the Microgrid from the grid-tied configuration. The further operational experiment achieved islanding at a specific load dependence on the building grid such that this load shedding scheme is no longer required.

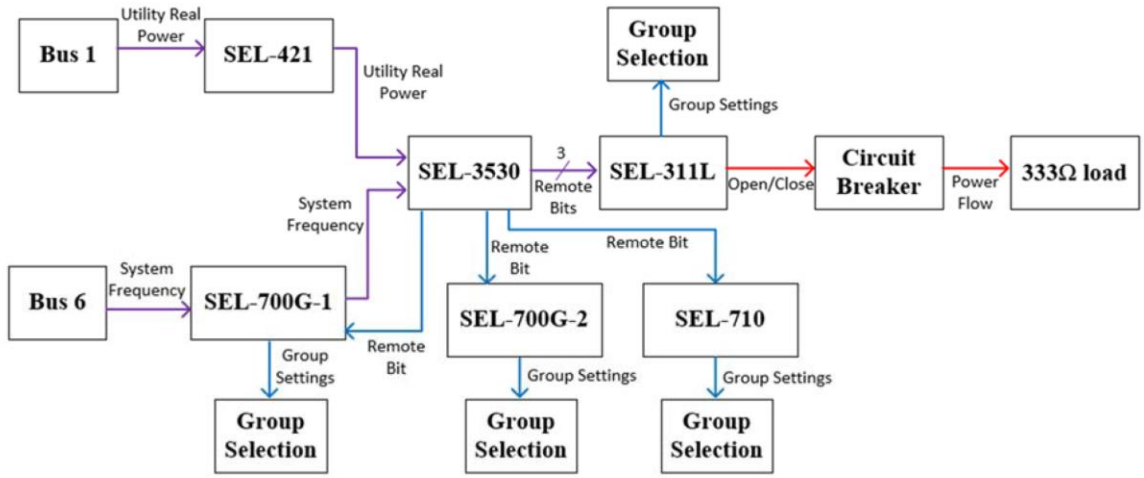


Figure 8. Existing RTAC Signal Flow Diagram

Most SEL microprocessor relays (SEL-710, SEL-700G, SEL-751, and SELL-351) in the Microgrid have various group settings available except for the SEL-587. The RTAC automatically switches the relay groups depending on the system configuration. The RTAC collects real power data from the SEL-421 Protection, Automation, and Control System relay to determine the utility grid's status. When power flow exceeds 80W, the utility grid is considered on and vice versa when the utility grid's power falls below 80W. This wattage threshold is calculated as the total power consumption of the two transformers corresponding to the magnetization current. Hence, utility bus voltage must be present for the breaker between the Microgrid and the utility grid to close, allowing magnetization current to flow. In addition, during the synchronization process to the utility, the SEL-421 Protection, Automation, and Control System relay utilizes the synchronism-check element to facilitate breaking closure automatically. The Synchronism-check element checks for the phase difference and voltage magnitude difference between the Microgrid and the utility bus. Once all conditions are met, the SEL-421 will automatically close the breaker. A similar process applies to the generator synchronization process using the SEL-700G.

Table 4. Relay Group Selection

Configuration	**Relay**	**Active Group**
Utility Connected	SEL-387E	2
	SEL-311L (line 1)	2
	SEL-710	2
	SEL-311L (line 2)	2
	SEL-587	N/A
	SEL-700G (generator 1)	2
	SEL-700G (generator 2)	2
	SEL-421	2
Islanded	SEL-387E	2
	SEL-311L (line 1)	2
	SEL-710	1
	SEL-311L (line 2)	1
	SEL-587	N/A
	SEL-700G (generator 1)	1
	SEL-700G (generator 2)	1
	SEL-421	2

4.4 LOAD SHEDDING

The existing automation capability has successfully ensured the stable and flexible operation of the Microgrid during the generator synchronization process. However, with the introduction of renewable energy to the system, additional automation features must be implemented to account for voltage and power production fluctuation. This fluctuation becomes concerning when the Microgrid is in the islanded mode. For example, when the inverter and generators are concurrently powering the Microgrid, sudden cloud coverage over the solar panels can reduce the inverter's power output. The generators promptly pick up this load reduction. Depending on the load change magnitude, the generator frequency can decrease below the SEL-700G relay pick-up value and trip offline, causing a complete grid collapse. Note: the two synchronous generators do not have any automatic voltage regulating control and governor control. The generator's output voltage is manually controlled by the rheostat that supplies field voltage to the field winding while the governor of the prime mover controls the power.

To prevent a potential grid collapse, active load shedding must occur while the grid is islanded to reduce the resistive load, thus, increase the grid frequency. The RTAC receives a frequency signal from the SEL-700G. There are two low-frequency thresholds implemented to provide the initial warnings before the actual load shedding occurs. This warning feature is incorporated into the annunciator panel, see Table 5. When the generator's frequency falls below 59.7 Hz (1791 RPM), the RTAC sends a signal to the SEL-311L to trip the circuit breaker connecting one of the 166.67-ohm static loads to the Microgrid. The frequency threshold was experimentally chosen such that the grid can recover from the load shedding without a generator trip.

```
//New Load Shedding Scheme with Annunciation
IF (MICROGRID_HMI.SRBC_0089.operSet.ctlVal = TRUE) AND          // Islanded mode (See Annunciator logic for details)
    (MICROGRID_HMI.SRBC_0082.operSet.ctlVal = FALSE) THEN        // Inverter synched (See Annunciator logic for details)
    IF  FREQ < 60 THEN                                           // Frequency < 59.967 Hz or ~1799 RPM THEN
        MICROGRID_HMI.SRBC_00103.operSet.ctlVal := TRUE;         // Safe Power Margin Alarm MD-07 On
        MICROGRID_HMI.SRBC_00103.operClear.ctlVal := FALSE;
        IF(FREQ < 59.867 AND                                     // Frequency < 59.867 Hz or ~1796 RPM THEN
         FREQ > 59.7) THEN                                       // Frequency > 59.7 Hz or ~1791 RPM THEN
        MICROGRID_HMI.SRBC_00103.operSet.ctlVal := TRUE;         // Safe Power Margin Alarm MD-07 ON
        MICROGRID_HMI.SRBC_00103.operClear.ctlVal := FALSE;
        MICROGRID_HMI.SRBC_00102.operSet.ctlVal := TRUE;         // Islanding Safe Alarm MC-07 ON
        MICROGRID_HMI.SRBC_00102.operClear.ctlVal := FALSE;
        ELSIF (FREQ < 59.7) THEN                                 // Frequency < 59.7 Hz or ~1791 RPM THEN
        SEL_311L_2_SEL.FO_RB_RB1.operClear.ctlVal := FALSE;      // LOAD SHEDDING
        SEL_311L_2_SEL.FO_RB_RB1.operSet.ctlVal := TRUE;
        END_IF
    ELSE
        MICROGRID_HMI.SRBC_00102.operSet.ctlVal := FALSE;        // Safe Power Margin Alarm MA-07 OFF
        MICROGRID_HMI.SRBC_00102.operClear.ctlVal := TRUE;
        MICROGRID_HMI.SRBC_00103.operSet.ctlVal := FALSE;        // Safe Power Margin Alarm MA-07 OFF
        MICROGRID_HMI.SRBC_00103.operClear.ctlVal := TRUE;
    END_IF
ELSE
        MICROGRID_HMI.SRBC_00102.operSet.ctlVal := FALSE;        // Safe Power Margin Alarm MA-07 OFF
        MICROGRID_HMI.SRBC_00102.operClear.ctlVal := TRUE;
        MICROGRID_HMI.SRBC_00103.operSet.ctlVal := FALSE;        // Safe Power Margin Alarm MA-07 OFF
        MICROGRID_HMI.SRBC_00103.operClear.ctlVal := TRUE;
        SEL_311L_2_SEL.FO_RB_RB1.operClear.ctlVal := TRUE;       // NO LOAD SHEDDING
        SEL_311L_2_SEL.FO_RB_RB1.operSet.ctlVal := FALSE;
END_IF
```

Figure 8. Load Shedding Scheme Code (RTAC)

Table 5. Load Shedding Thresholds and Annunciation

	Condition(s)	Normal State	Alarm State
Threshold #1	< 60 Hz (1800 RPM)	SAFE POWER MARGIN	INSUFFICIENT POWER / FREQ UNSTABLE
Threshold #2	< 59.867 Hz (1796 RPM)	**ISLANDING SAFE**	**ISLANDING ABORT**
Load Shedding*	< 59.7 RPM (1791 RPM)	STATIC LOAD CONNECTED	LOAD SHED

* All three alarms are triggered when load shedding occurs.

4.5 LOAD SHEDDING TEST

The load shedding test evaluates the new load shedding scheme's performance in its ability to keep the Microgrid energized when the inverter power drops below the threshold. Six case studies at various power configurations were chosen to ensure load shedding will work regardless of the generation unit's initial power contribution and the amount of frequency support from each synchronous generator. The test was conducted following the initial conditions as stated in Table 6 when the Microgrid was operating in the islanded mode. Figure 11 details the parameters being monitored in real-time while conducting the test. To lower the Microgrid frequency, the solar panels were tilted away from their perpendicular position to the sun to reduce energy harvesting, thus output power. The generators' field current and governor position were kept untouched. Figure 9 and Figure 10 captured the APsystem microinverter's output power during testing.

Figure 9. Load Shedding Test - Microinverter Power Data (Day 1)

Figure 10. Load Shedding Test - Microinverter Power Data (Day 2)

From the test results in Table 1, the Microgrid remained fully operational with the load shedding scheme enabled. In cases #1 and #2, the resistive load was shed as expected and prevented the frequency from further reduction. The microinverter remained online throughout the evolution. The frequency right after load shedding increased to approximately 60.2 Hz (1806 RPM). In cases #4 to #6, the Microgrid was unable to recover with load shedding disabled. The frequency continued to decrease as the inverter power decreased. The generators tripped offline by the SEL-700G with underfrequency pickup value at 59.58 Hz (1787 RPM). Case study 3 was conducted to obtain an operational understanding of the system. The Microgrid collapsed due to the undervoltage trip of the generators. Another attempt (not documented in this report) was made to replicate case study #3 with manual interference to raise the generator voltage by injecting more field current. However, this additional field current injection shortly exceeded the limit of the potentiometer. In conclusion, the Microgrid cannot operate stably with adequate voltage support from a single generator.

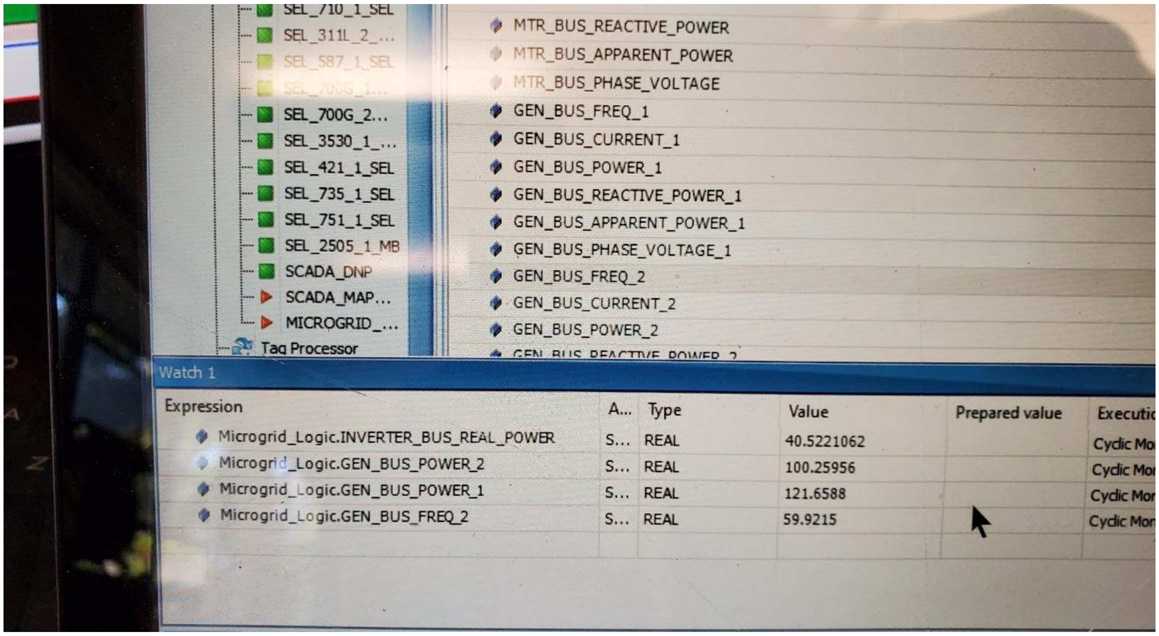


Figure 11. Monitored Parameters during the Load Shedding Test (RTAC software)

Table 6. Load Shedding Test Cases

	Case	**Initial Gen. #1 Power (W)**	**Initial Gen. #2 Power (W)**	**Initial Invr. Power (W)**	**Invr. Power when load sheds (W)**	**Invr. Power when grid collapses (W)**
Load Shedding Enabled	1	85	93	161	108	N/A
	2	130	46	166	112	N/A
	3	0	220	97	N/A	66
Load Shedding disabled	4	86	87	167	N/A	98
	5	143	33	165	N/A	100
	6	137	46	158	N/A	94

4.6 ADDITIONAL AUTOMATION FEATURES

Additional automation features were incorporated into Microgrid, such as the Emergency Safety Shutdown (ESS) system and the remote group setting change. The ESS system was designed to completely and safely de-energize the Microgrid; see Chapter 6 for details of the design and operation. The remote group setting change demonstrates a proof of concept to change an SEL relay within the Microgrid via the RTAC using a non-SEL device. Such capability is necessary to combat wildfire risk in the electrical system; see Chapter 4.3 for details.

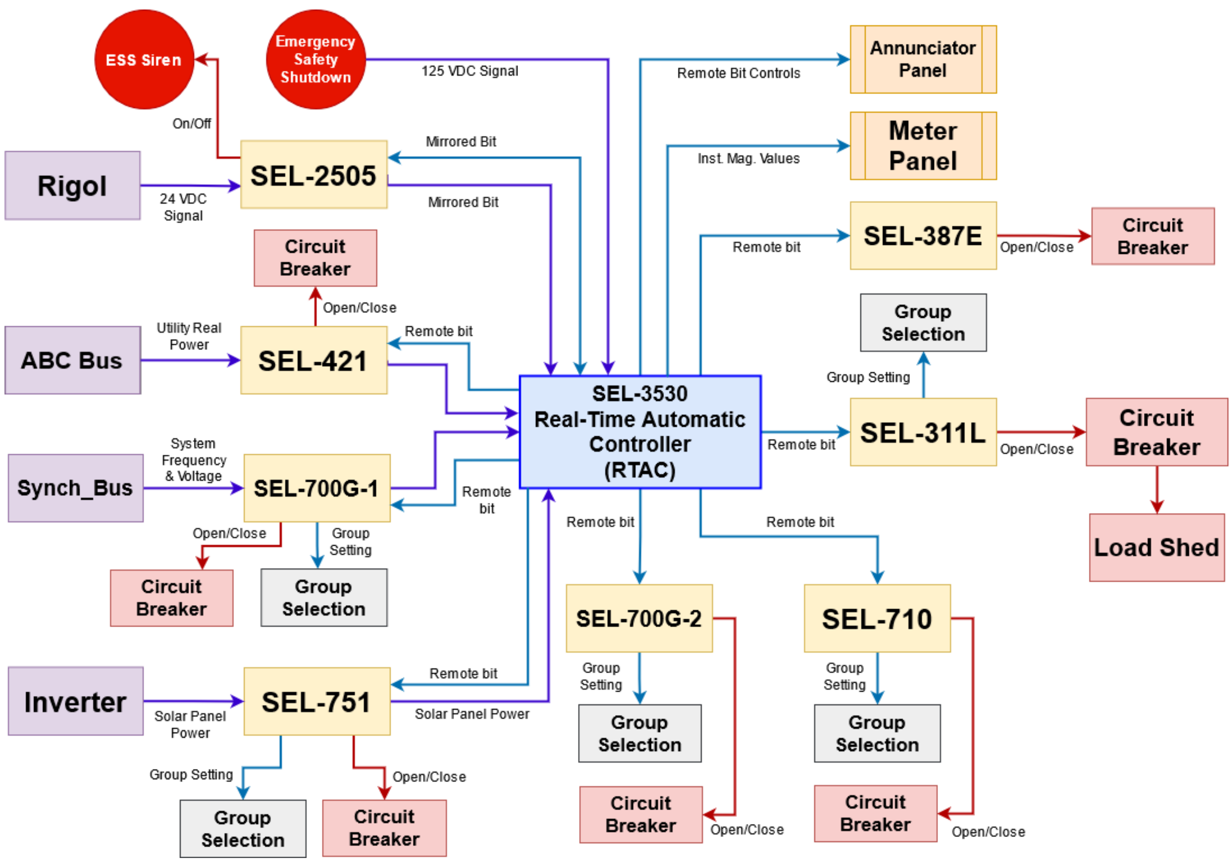


Figure 12. New RTAC Signal Flow Diagram

CHAPTER 5. ANNUNCIATION

Operating the Microgrid can be difficult, especially when synchronizing the generation sources or troubleshooting various grid conditions. The uneasy operation is contributed by the lack of valuable indications and the reliance on an overwhelming number of meters (speedometer, voltage meter, P/Q mete, etc.) at once. In addition, the Microgrid has relays and breakers' display facing both sides of lab benches 5 and 6 that make it impossible for situational awareness. All the mentioned elements can increase human errors, jeopardize safety and lead to unwanted grid operating conditions or equipment damage. Therefore, an annunciator panel and meter panel are necessary to guide the students and faculties, thus ensuring safe and efficient control of the Microgrid.

5.1 ANNUNCIATOR AND METER PANEL

The traditional annunciator panel consists of arrays of indicator lamps. Each indicator associates with circuitry designed to draw human attention when a process changes into an abnormal state. A typical indicator will change color and or blink and is accompanied by an audible alarm when abnormalities present. Figure 13 (Left) shows a traditional annunciator panel. Modern annunciator panel is displayed on an LCD screen and sometimes touchscreen, Figure 13 (Right). LCD screens are becoming popular due to the unique advantages, such as the touchscreen, customizable configuration, and expandability. As such, an LCD TV will play display the annunciator panel and meter panel to support Microgrid operation.

Figure 13. Traditional Annunciator (Left) and LCD Annunciator (Right)

5.2 ACSELERATOR DIAGRAM BUILDER SEL-5035

Unlike traditional annunciators whose operation solely relies on hardwires from the targeted process's circuitry, modern counterparts require software to support design and human interface. The Microgrid annunciator panel and meter panel are designed using AcSELerator Diagram Builder SEL-5035 software by Schweitzer Engineering Laboratories, Figure 14. All tags are imported from the SEL-3530 RTAC. Each tag represents a unique data point of various types depending on the specific need. For example, a voltage or current display would require an analog data point (type MV attribute), whereas breaker control data would require a binary data point with pulse configuration and duration (type SPC attribute). Detailed information on each tag type can be found in the SEL-3530 Real-time Automation Controller Instruction Manual [7]. For the Microgrid annunciator's purpose, all tags are in binary status (type SPS attribute). Each tag offers a true or false state customized to represent a normal or alarm state of the targeted process. SEL-5035 software offers a pre-built annunciator control block with or without acknowledgment capability. The meter panel is placed next to the annunciator panel on the LCD and consists of analog data points representing the microgrid's real-time metering data.

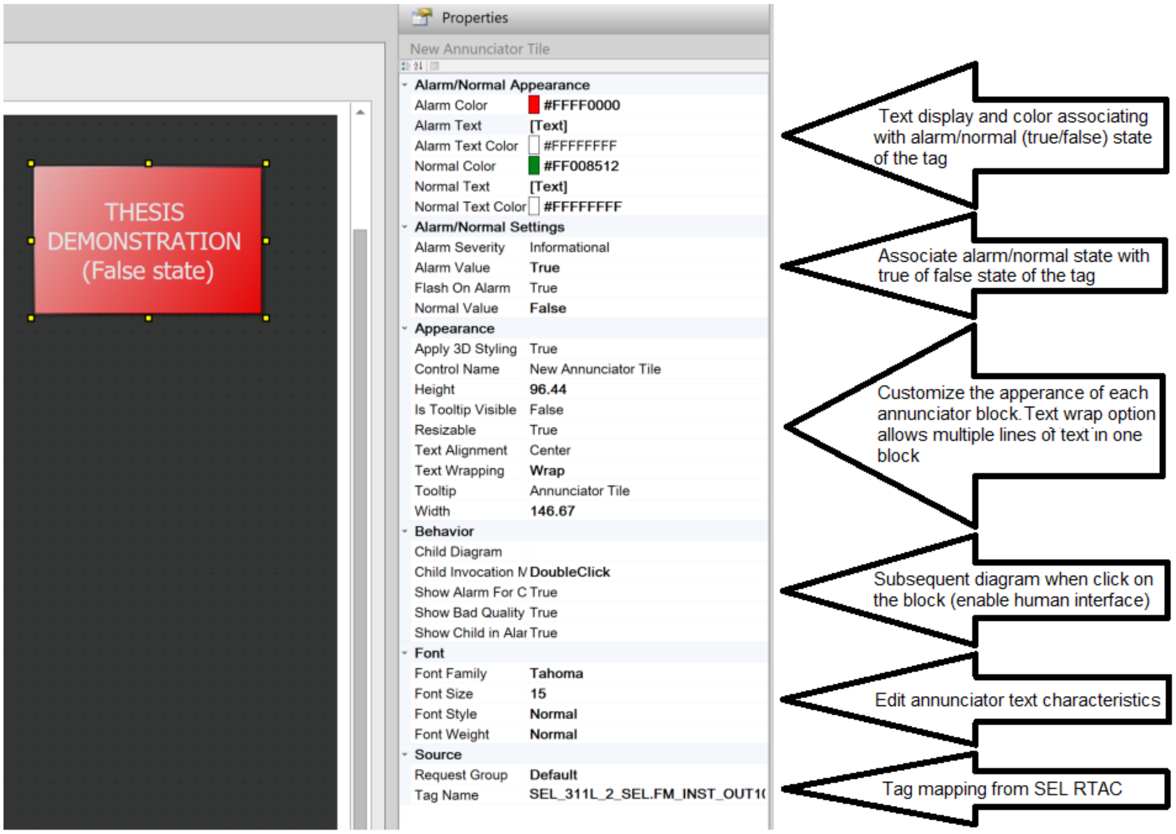


Figure 14. Diagram Builder Annunciator Properties and Annotation

In the Microgrid annunciator panel, each annunciator has a designated color to display the level of severity. Table 7 contains detailed characteristics of each annunciator level. Once all annunciators are assigned appropriate tags, they are organized into specific process groups (Generator #1, Generator #2, Utility). Figure 15 and Figure 16 show the final Microgrid Annunciator Panel in Normal and Alarm state as seen in the SEL-5035 Diagram Builder Software.

Table 7. Annunciator Characteristics

Severity Level	Annunciator Color	Annunciator Text	Visual Effect
Normal	GREEN	White	Solid
Normal/Not Preferred	GREEN	White	Flash
Abnormal	RED	White	Flash
Dangerous	YELLOW	Red	Flash

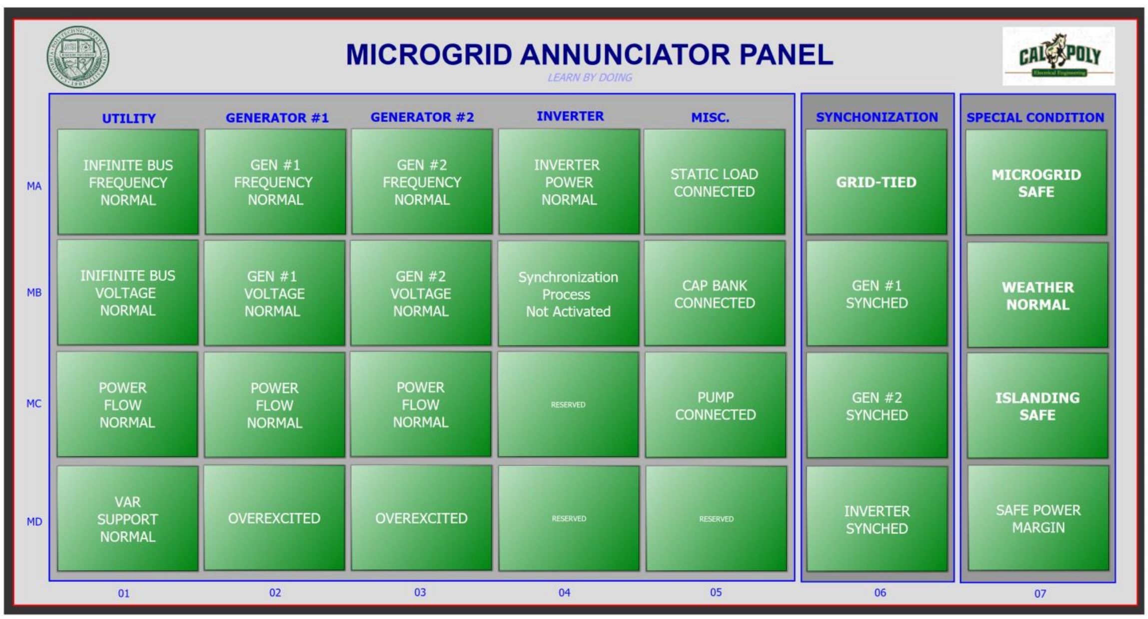


Figure 15. Microgrid Annunciator Panel in Normal State (SEL-5035 Software)

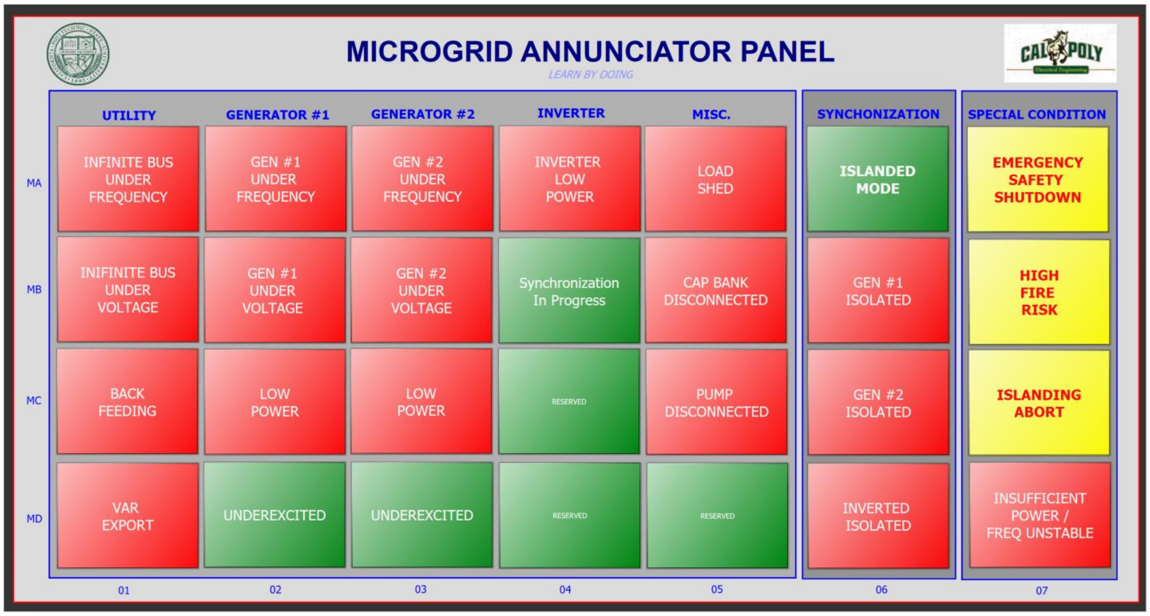


Figure 16. Microgrid Annunciator Panel in Alarm State (SEL-5035 Software)

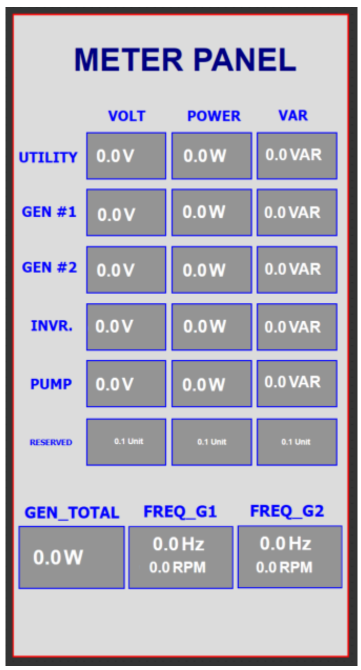


Figure 17. Microgrid Meter Panel

5.3 SEL-3530 RTAC TAG MAPPING

For the annunciator panel, each type SPS tag associates with a process or a parameter being monitored. Once a process or a parameter changes into an abnormal state, the type SPS tag will become "true" and lead to an "alarm" state of the annunciator. Two tag lists in the RTAC support the annunciator's function: MICROGRID_HMI (Virtual Tag List) and SCADA_MAP_DNP (DNP Server Shared Map). The MICROGRID_HMI tag list is created to provide SEL Remote Bit Controls (SRBC) tag group that support operSPC tags to be used in the user logic program whose algorithm controls the state of each tag. Chapter 5.4 provides a detailed algorithm for each annunciator tag. It is essential to be aware type operSPC tag must be dotted with the attribute "ctlVal" to become type "BOOL" and associable with type SPS tags. The MICROGIRD_HMI list also acts as source expression tags to be mapped with destination tags within the tag processor. The SCADA_MAP_DNP tag list provides SPS tags and acts as a destination tag mapped to each annunciator control block. The tag processor is a repository where source expression tags and destination tags are mapped; see Figure 16. Mapped tags are grouped into their associating annunciator category and share the same tag number for tracking ease. Each annunciator is given a unique ID corresponding grid map of the annunciator panel in Figure 15.

The meter panel, Figure 17, takes advantage of the built-in analog data points within the SEL relays with tag type MV (Measure Value). Most data points on the meter panel are directly tied to type MV tags without a tag processor. For example, generator #1’s voltage value associates with tag SEL_700G_1_SEL.FM_INST_VAX from the SEL-700G1. As seen in Figure 24, exceptional data points that require further calculation are the total power generation, generator speed in RPM, utility voltage, and inverter bus voltage. Such calculation is needed, for example, to convert frequency in hertz to speed in RPM or the sum of all generating units. Appendix K, Table 8 provides comprehensive information on the annunciator panel.

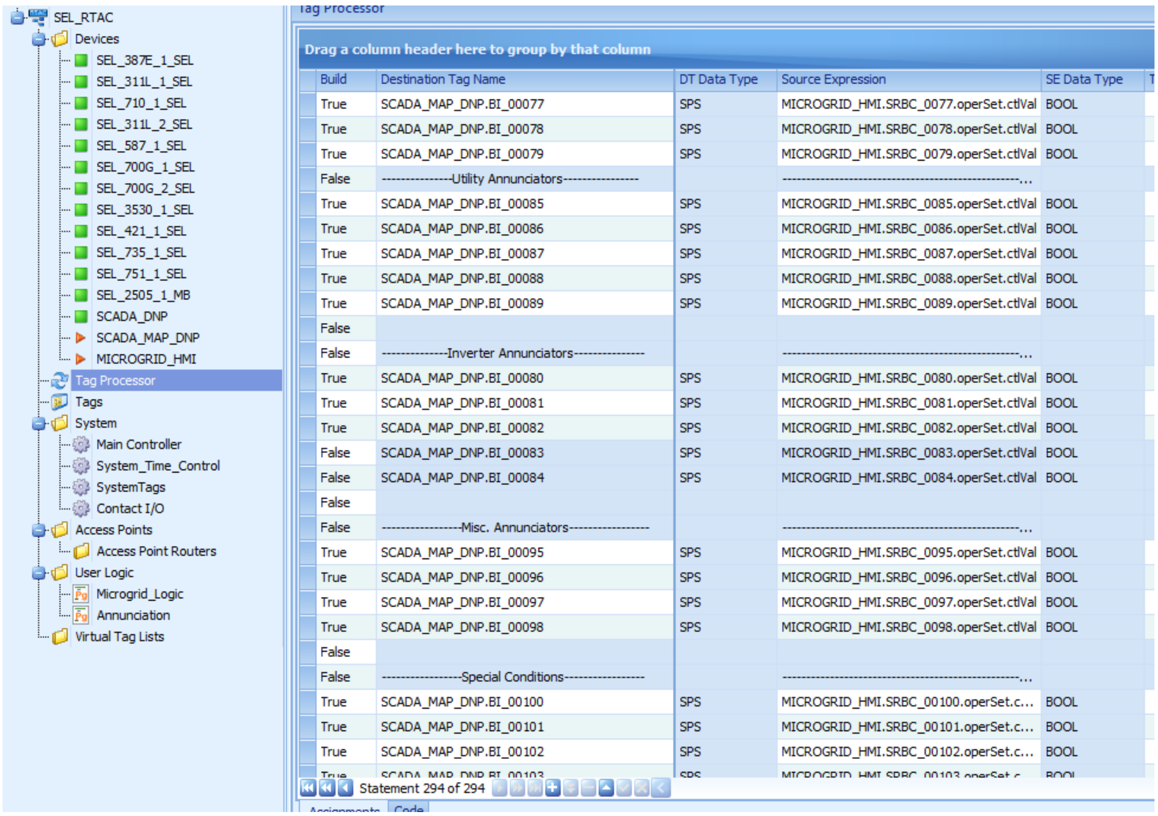


Figure 18. Tag Processor (SEL AcSELerator RTAC software)

5.4 SEL-3530 RTAC LOGIC PROGRAM

For tags to properly change state, they are either embedded into a process's code or have a designated algorithm to be triggered. All program for the Microgrid is written in structured text program under the user logic. The annunciation logic program is separate from the main program for coding convenience and ease of alarm troubleshooting purposes. The special condition annunciator tags are embedded into the main program logic. For example, MA-07 tag is a part of the ESS code, while MC-07 and MD-07 tags are embedded within the load shedding scheme code, Figure 8. All other annunciator tags have a dedicated algorithm. Figure 19 to Figure 23 detail the annunciator program code in SEL AcSELerator RTAC software. Figure 24 provides the calculation code for the meter panel that combines all generated power to form the total power, conversion code to convert the generator frequency to speed, and line-to-line voltages to line-to-ground voltages at the inverter and utility buses.

```
//------------------MICROGRID ANNUNCIATOR PANEL in HMI----------------------//

// Generator #2 ALARMS (SEL-700G2)
IF (SEL_700G_2_SEL.FM_INST_FREQX.instMag < 59.83) OR        // FREQUENCY ALARM MA-03
    SEL_700G_2_SEL.FM_INST_VAX.instMag < 5 THEN
    MICROGRID_HMI.SRBC_0065.operSet.ctlVal := TRUE;
    MICROGRID_HMI.SRBC_0065.operClear.ctlVal := FALSE;
ELSE
    MICROGRID_HMI.SRBC_0065.operSet.ctlVal := FALSE;
    MICROGRID_HMI.SRBC_0065.operClear.ctlVal := TRUE;
END_IF

IF (SEL_700G_2_SEL.FM_INST_VAX.instMag < 114) THEN          // VOLTAGE ALARM MB-03
    MICROGRID_HMI.SRBC_0066.operSet.ctlVal := TRUE;
    MICROGRID_HMI.SRBC_0066.operClear.ctlVal := FALSE;
ELSE
    MICROGRID_HMI.SRBC_0066.operSet.ctlVal := FALSE;
    MICROGRID_HMI.SRBC_0066.operClear.ctlVal := TRUE;
END_IF

IF (SEL_700G_2_SEL.FM_INST_P3X.instMag < 30) THEN           // POWER FLOW ALARM MC-03
    MICROGRID_HMI.SRBC_0067.operSet.ctlVal := TRUE;
    MICROGRID_HMI.SRBC_0067.operClear.ctlVal := FALSE;
ELSE
    MICROGRID_HMI.SRBC_0067.operSet.ctlVal := FALSE;
    MICROGRID_HMI.SRBC_0067.operClear.ctlVal := TRUE;
END_IF

IF (SEL_700G_2_SEL.FM_INST_Q3X.instMag < 0) THEN            // OVEREXCITED ALARM MD-03
    MICROGRID_HMI.SRBC_0068.operSet.ctlVal := TRUE;
    MICROGRID_HMI.SRBC_0068.operClear.ctlVal := FALSE;
ELSE
    MICROGRID_HMI.SRBC_0068.operSet.ctlVal := FALSE;
    MICROGRID_HMI.SRBC_0068.operClear.ctlVal := TRUE;
END_IF
```

Figure 19. Annunciator RTAC Program Code - 1/7

```
// Generator #1 ALARMS (SEL-700G1)
IF (SEL_700G_1_SEL.FM_INST_FREQX.instMag < 59.83) OR        // FREQUENCY ALARM MA-02
    SEL_700G_1_SEL.FM_INST_VAX.instMag < 5 THEN
    MICROGRID_HMI.SRBC_0075.operSet.ctlVal := TRUE;
    MICROGRID_HMI.SRBC_0075.operClear.ctlVal := FALSE;
ELSE
    MICROGRID_HMI.SRBC_0075.operSet.ctlVal := FALSE;
    MICROGRID_HMI.SRBC_0075.operClear.ctlVal := TRUE;
END_IF

IF (SEL_700G_1_SEL.FM_INST_VAX.instMag < 114) THEN          // VOLTAGE ALARM MB-02
    MICROGRID_HMI.SRBC_0076.operSet.ctlVal := TRUE;
    MICROGRID_HMI.SRBC_0076.operClear.ctlVal := FALSE;
ELSE
    MICROGRID_HMI.SRBC_0076.operSet.ctlVal := FALSE;
    MICROGRID_HMI.SRBC_0076.operClear.ctlVal := TRUE;
END_IF

IF (SEL_700G_1_SEL.FM_INST_P3X.instMag < 30) THEN           // POWER FLOW ALARM MC-02
    MICROGRID_HMI.SRBC_0077.operSet.ctlVal := TRUE;
    MICROGRID_HMI.SRBC_0077.operClear.ctlVal := FALSE;
ELSE
    MICROGRID_HMI.SRBC_0077.operSet.ctlVal := FALSE;
    MICROGRID_HMI.SRBC_0077.operClear.ctlVal := TRUE;
END_IF

IF (SEL_700G_1_SEL.FM_INST_Q3X.instMag < 0) THEN            // OVEREXCITED ALARM MD-02
    MICROGRID_HMI.SRBC_0078.operSet.ctlVal := TRUE;
    MICROGRID_HMI.SRBC_0078.operClear.ctlVal := FALSE;
ELSE
    MICROGRID_HMI.SRBC_0078.operSet.ctlVal := FALSE;
    MICROGRID_HMI.SRBC_0078.operClear.ctlVal := TRUE;
END_IF
```

Figure 20. Annunciator RTAC Program Code - 2/7

```
// UTILITY ALARMS (SEL-421)
IF (SEL_421_1_SEL.FM_INST_FREQ.instMag < 59.9) OR           // FREQUENCY ALARM MA-01
    (SEL_421_1_SEL.FM_INST_VA.instCVal.mag < 5)THEN
    MICROGRID_HMI.SRBC_0085.operSet.ctlVal := TRUE;
    MICROGRID_HMI.SRBC_0085.operClear.ctlVal := FALSE;
ELSE
    MICROGRID_HMI.SRBC_0085.operSet.ctlVal := FALSE;
    MICROGRID_HMI.SRBC_0085.operClear.ctlVal := TRUE;
END_IF

IF (SEL_421_1_SEL.FM_INST_VA.instCVal.mag < 114) THEN       // UNDERVOLTAGE ALARM MB-01
    MICROGRID_HMI.SRBC_0086.operSet.ctlVal := TRUE;
    MICROGRID_HMI.SRBC_0086.operClear.ctlVal := FALSE;
ELSE
    MICROGRID_HMI.SRBC_0086.operSet.ctlVal := FALSE;
    MICROGRID_HMI.SRBC_0086.operClear.ctlVal := TRUE;
END_IF

IF (SEL_421_1_SEL.FM_INST_P_WATTS.instMag < 1) THEN         // POWER FLOW ALARM MC-01
    MICROGRID_HMI.SRBC_0087.operSet.ctlVal := TRUE;
    MICROGRID_HMI.SRBC_0087.operClear.ctlVal := FALSE;
ELSE
    MICROGRID_HMI.SRBC_0087.operSet.ctlVal := FALSE;
    MICROGRID_HMI.SRBC_0087.operClear.ctlVal := TRUE;
END_IF

IF (SEL_421_1_SEL.FM_INST_Q_VARS.instMag < 1) THEN          // OVEREXCITED ALARM MD-01
    MICROGRID_HMI.SRBC_0088.operSet.ctlVal := TRUE;
    MICROGRID_HMI.SRBC_0088.operClear.ctlVal := FALSE;
ELSE
    MICROGRID_HMI.SRBC_0088.operSet.ctlVal := FALSE;
    MICROGRID_HMI.SRBC_0088.operClear.ctlVal := TRUE;
END_IF
```

Figure 21. Annunciator RTAC Program Code - 3/7

```
// MISC.
IF SystemTags.IN101.stVal = FALSE THEN                    // STATIC LOAD CONNECTED ALARM MA-05
    MICROGRID_HMI.SRBC_0095.operSet.ctlVal := TRUE;
    MICROGRID_HMI.SRBC_0095.operClear.ctlVal := FALSE;
ELSE
    MICROGRID_HMI.SRBC_0095.operSet.ctlVal := FALSE;
    MICROGRID_HMI.SRBC_0095.operClear.ctlVal := TRUE;
END_IF

IF  (ABS(SEL_710_1_SEL.FM_INST_P.instMag) < 5)  OR        // CAP BANK CONNECTED ALARM MB-05
        (SEL_710_1_SEL.FM_INST_VA.instMag < 5) THEN
    MICROGRID_HMI.SRBC_0096.operSet.ctlVal := TRUE;
    MICROGRID_HMI.SRBC_0096.operClear.ctlVal := FALSE;
    MICROGRID_HMI.SRBC_0097.operSet.ctlVal := TRUE;       // PUMP CONNECTED ALARM MC-05
    MICROGRID_HMI.SRBC_0097.operClear.ctlVal := TRUE;
ELSE
    MICROGRID_HMI.SRBC_0097.operSet.ctlVal := FALSE;
    MICROGRID_HMI.SRBC_0097.operClear.ctlVal := TRUE;
    MICROGRID_HMI.SRBC_0096.operSet.ctlVal := FALSE;
    MICROGRID_HMI.SRBC_0096.operClear.ctlVal := TRUE;
END_IF
```

Figure 22. Annunciator RTAC Program Code - 5/6

```
// SYNCHRONIZATION
IF  (ABS(SEL_421_1_SEL.FM_INST_P_WATTS.instMag) > 0.5) AND  // GRID-TIED ALARM MA-06
    ((SEL_421_1_SEL.FM_INST_VB.instCVal.mag) > 100)  THEN
    MICROGRID_HMI.SRBC_0089.operSet.ctlVal := FALSE;
    MICROGRID_HMI.SRBC_0089.operClear.ctlVal := TRUE;

ELSE
    MICROGRID_HMI.SRBC_0089.operSet.ctlVal := TRUE;
    MICROGRID_HMI.SRBC_0089.operClear.ctlVal := FALSE;
END_IF

IF  (SEL_700G_1_SEL.FM_INST_VAX.instMag < 5) OR
    (ABS(SEL_700G_1_SEL.FM_INST_VAX.instMag -              // SYNCH ALARM MB-06
        SEL_700G_1_SEL.FM_INST_VAY.instMag) > 0.1) AND
    (ABS(SEL_700G_1_SEL.FM_INST_P3X.instMag) < 1)  THEN
    MICROGRID_HMI.SRBC_0079.operSet.ctlVal := TRUE;
    MICROGRID_HMI.SRBC_0079.operClear.ctlVal := FALSE;
ELSE
    MICROGRID_HMI.SRBC_0079.operSet.ctlVal := FALSE;
    MICROGRID_HMI.SRBC_0079.operClear.ctlVal := TRUE;
END_IF

IF  (SEL_700G_2_SEL.FM_INST_VAX.instMag < 5) OR            // SYNCH ALARM MC-06
    (ABS(SEL_700G_2_SEL.FM_INST_VAX.instMag -
        SEL_700G_2_SEL.FM_INST_VAY.instMag) > 0.1) AND
    (ABS(SEL_700G_2_SEL.FM_INST_P3X.instMag) < 1)  THEN
    MICROGRID_HMI.SRBC_0069.operSet.ctlVal := TRUE;
    MICROGRID_HMI.SRBC_0069.operClear.ctlVal := FALSE;
ELSE
    MICROGRID_HMI.SRBC_0069.operSet.ctlVal := FALSE;
    MICROGRID_HMI.SRBC_0069.operClear.ctlVal := TRUE;
END_IF

IF (SEL_751_1_SEL.FM_INST_P.instMag < 1)  THEN           // SYNCH ALARM MD-06
    MICROGRID_HMI.SRBC_0081.operSet.ctlVal := TRUE;
    MICROGRID_HMI.SRBC_0081.operClear.ctlVal := FALSE;
ELSE
    MICROGRID_HMI.SRBC_0081.operSet.ctlVal := FALSE;
    MICROGRID_HMI.SRBC_0081.operClear.ctlVal := TRUE;
END_IF
```

Figure 23. Annunciator RTAC Program Code - 6/6

```
//--------------------METER PANEL in HMI-----------------------//
GEN_TOTAL := (SEL_700G_2_SEL.FM_INST_P3X.instMag           // Total generation
            + SEL_700G_1_SEL.FM_INST_P3X.instMag
            + SEL_751_1_SEL.FM_INST_P.instMag);
MICROGRID_HMI.APC_0140.status.instMag := GEN_TOTAL;
RPM_G1 := (((SEL_700G_1_SEL.FM_INST_FREQX.instMag)*60)/2);  // Generator #1 Speed in RPM
MICROGRID_HMI.APC_0141.status.instMag := RPM_G1;
RPM_G2 := (((SEL_700G_2_SEL.FM_INST_FREQX.instMag)*60)/2);  // Generator #1 Speed in RPM
SCADA_MAP_DNP.AI_00142.instMag := RPM_G2;
SCADA_MAP_DNP.AI_00143.instMag := SEL_421_1_SEL.FM_INST_VA.instCVal.mag; // Utility bus voltage
SCADA_MAP_DNP.AI_00144.instMag := ((SEL_751_1_SEL.FM_INST_VAB.instMag)/SQRT(3)); // Inverter bus voltage
```

Figure 24. Meter Panel RTAC Program Code

5.5 HUMAN MACHINE INTERFACE

The completed Microgrid Annunciator Panel in Diagram Builder needs to be exported to the RTAC to become accessible via SEL web-based portal and display each tag's online status. Figure 25 shows the export tool to upload the project. Once the Microgrid Annunciator Panel project has been successfully uploaded to the RTAC from a personal computer , a web interface is now accessible via https://172.29.131.1/home.sel using any browser. Figure 26. displays the main page

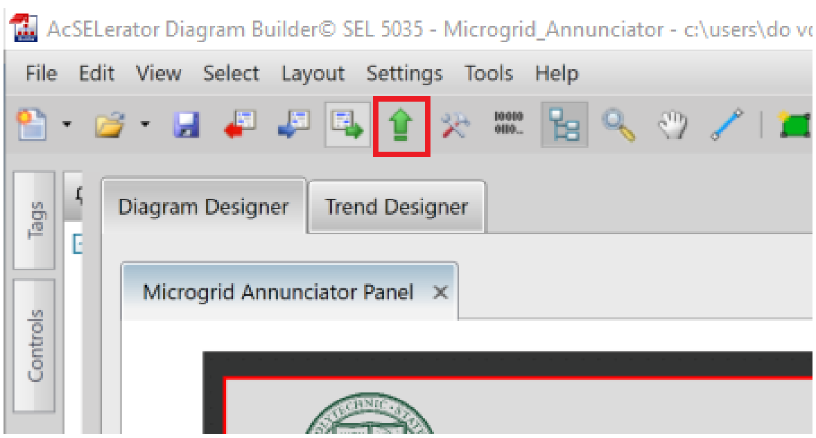


Figure 25. Project Export to RTAC (SEL-5035 Software)

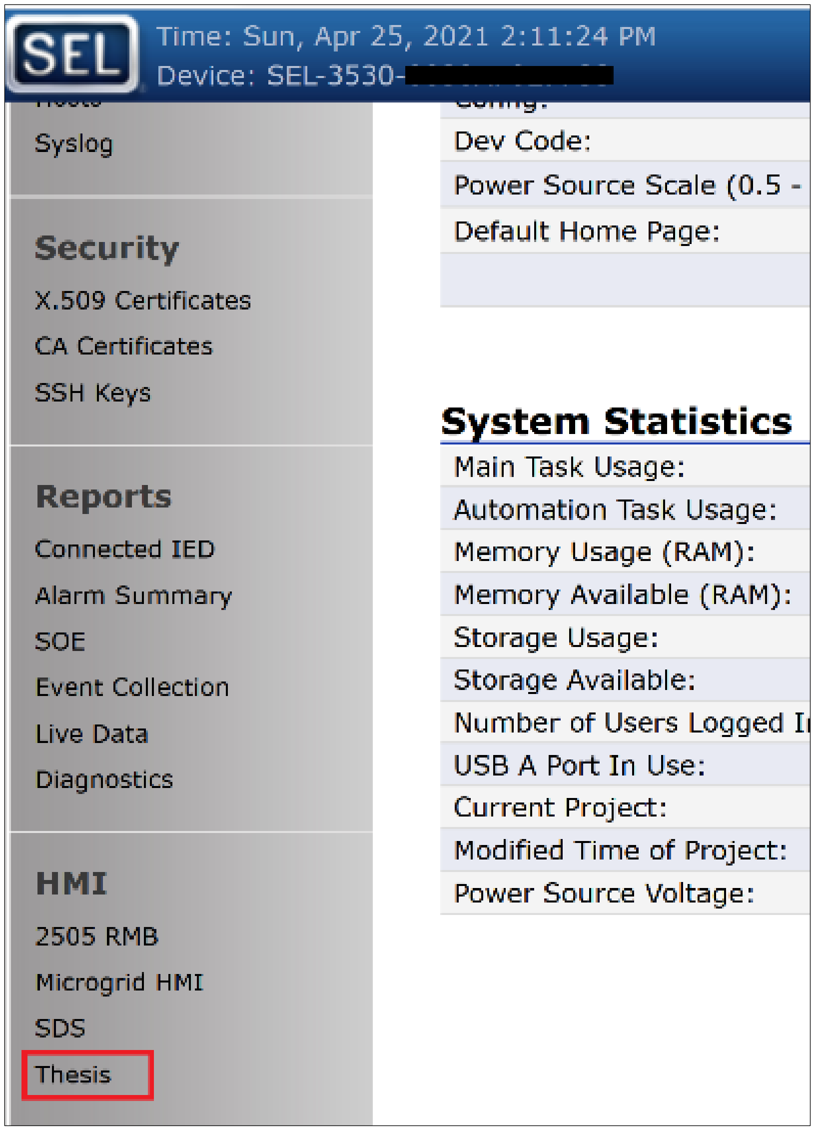


Figure 26. RTAC HMI Site

CHAPTER 6. EMERGENCY SAFETY SHUTDOWN (ESS)

Safety plays an utmost important role in power system. The Microgrid as a laboratory electrical system for the students and faculties to experiment is no exception. The power laboratory's existing safety features (Room 102), such as circuit breakers, switches, power lab control panel, are generally adequate. However, with much equipment (generator carts, invertor cart, breaker, etc.) surrounding the Microgrid benches, accessing those safety features can be difficult. Additional safety features must be added to enhance the overall safety of the Microgrid.

6.1 EXISTING SAFETY FEATURES

Figure 27 details steps to fully energize a lab bench in Room 102. The Microgrid energization process is after the lab bench energization process. Therefore, disabling any element within the lab bench energization sequence will interfere with the Microgrid's operation depending mode of operation, islanded versus grid-tied.

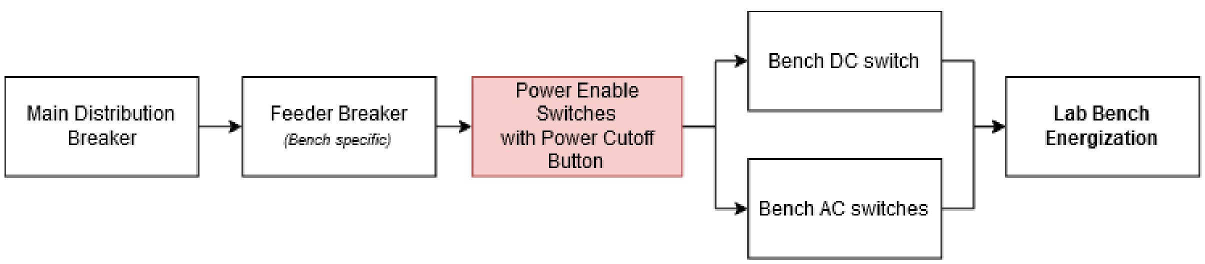


Figure 27. Lab Bench Energization Sequence.

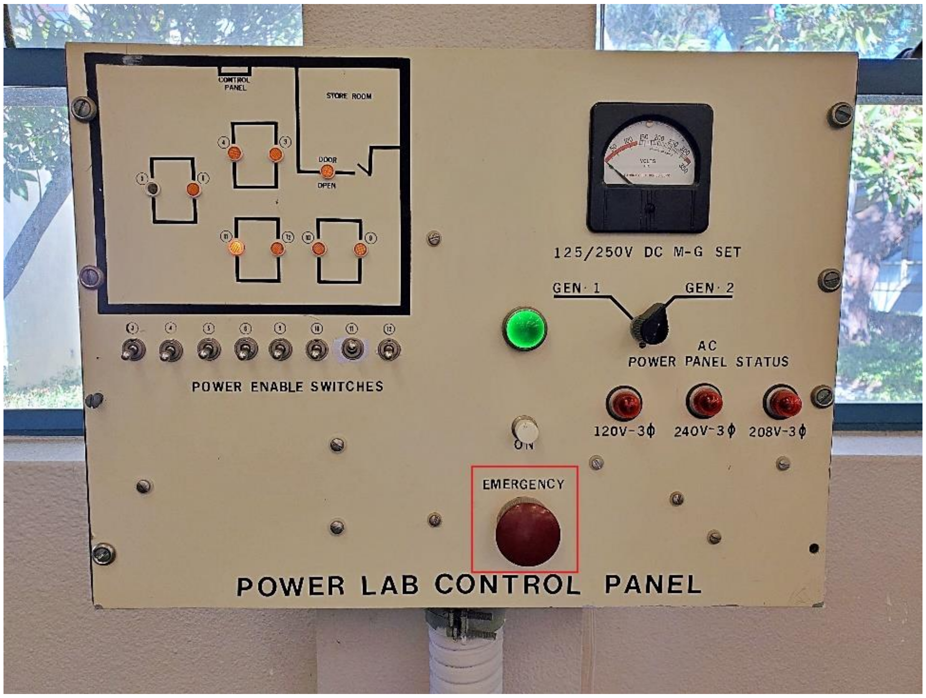


Figure 28. Power Lab Control Panel and Power Cutoff Button (Red)

Of the above elements, the Power Cutoff Button (red-colored box) is designed for emergency power shutoff purposes. Faculties instruct the students to push the button, Figure 28, should abnormalities occur while conducting any experiments. Depression of this button will immediately and completely de-energize all eight benches' DC and AC power. However, from the floor layout of room 102 (Figure 29), there is a significant distance (red dashed line) between the Microgrid to the power lab control panel to access the Power Cutoff Button. It is surveyed that the time taken to walk from Bench 5 to the panel is approximately 3 seconds and 4 seconds from Bench 6. A similar amount of time would be required to go from the Microgrid to the main feeder breakers, especially if the students are working from bench 5. One may attempt to de-energize the Microgrid by turning off the DC and AC switches. However, as seen in Figure 4 and Figure 29, access to these switches is blocked by the inverter and generator carts.

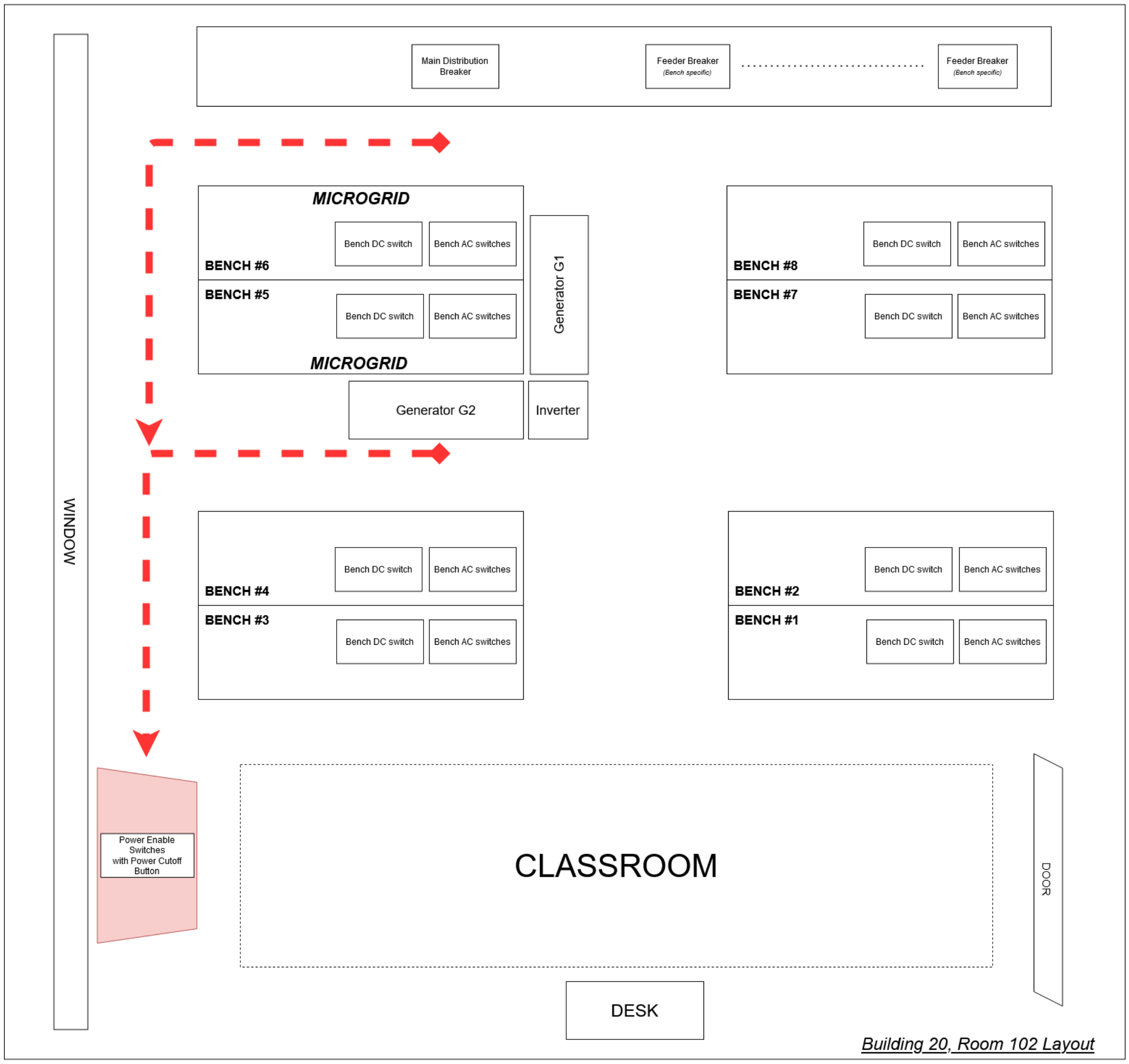


Figure 29. Room 102 Floor Layout

Furthermore, incident energy is defined as the amount of energy, at a prescribed distance from the equipment, released during an electrical arc event. The magnitude of fault current and clearing time directly correlates with the arc flash energy. As such, a travel time between 3 to 4 seconds from the Microgrid benches to the power cut-off button would be too long to de-energize the system and minimize the impact. Although the previous Microgrid projects have incorporated SEL protective relays to isolate faults automatically, not all cases and scenarios were thoroughly studied. A backup manual protection system is necessary if a fault or equipment malfunction occurs undetected.

Lastly, an earthquake or fire can strike at any moment with little to no warning; a safety system must be within reach to de-energize the live equipment to prevent cascaded catastrophe. An ESS system located at the Microgrid benches is necessary to provide an additional protection level for the students and faculties against any abnormalities.

6.2 ESS SYSTEM DESIGN

As seen in Figure 30, the ESS switches are the physical interface between the operator and the ESS system. Three switches are situated at three locations surrounding the Microgrid, Figure 31, where students and faculties are expected to conduct experiments.

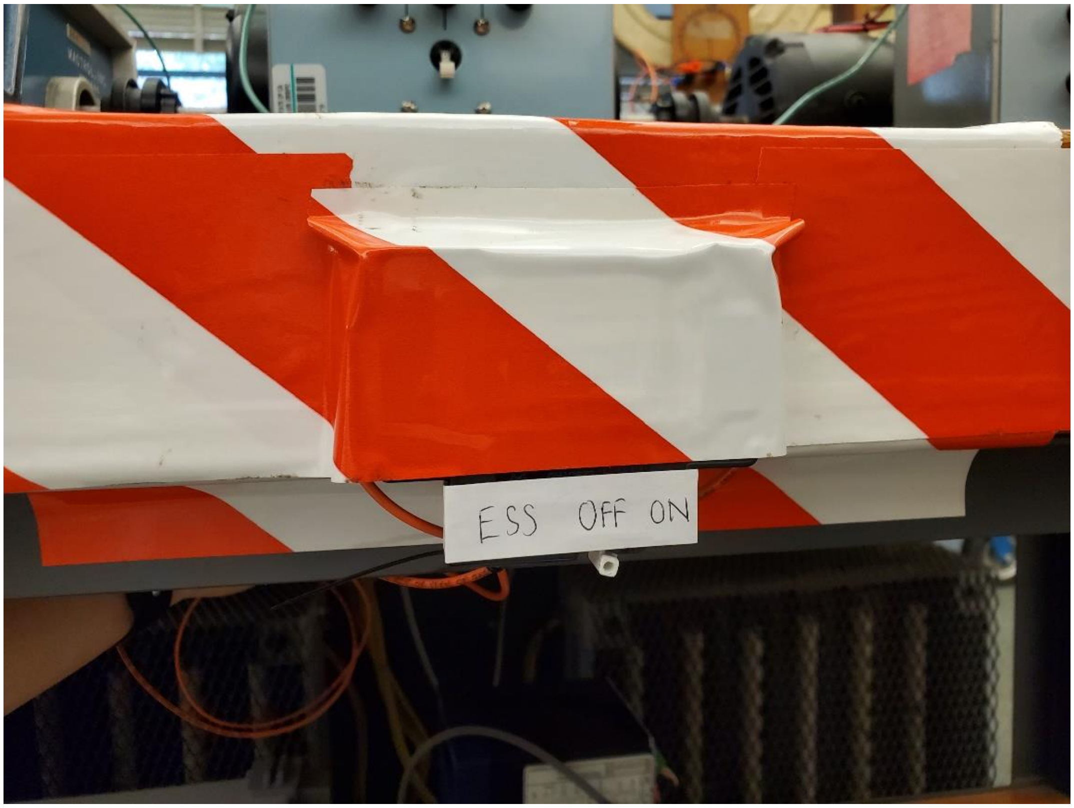


Figure 30. ESS Switch

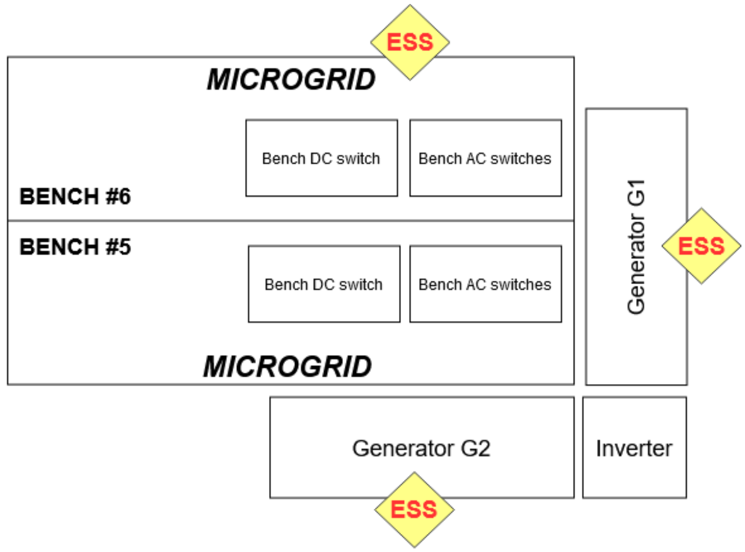


Figure 31. ESS Switches Location

Turning on any one of the three ESS switches will energize a 125 VDC bus that connects to the RTAC's optoisolated control inputs (IN201, IN202, and IN203). The controller will send a remote bit to the SEL-751, SEL-700G-1, SEL-700G-2, SEL-421, and SEL-387E to trip the associated breakers, see Figure 32 and Figure 33.

```
//Emergency Safety Shutdown (ESS)
IF IN201.stVal = TRUE OR                                        //ESS handle pulled
    IN202.stVal = TRUE OR
    IN203.stVal = TRUE THEN
    SEL_751_1_SEL.FO_RB_RB02.operSet.ctlVal := TRUE;            //Set RB2 for SEL-751 to open CB-SOLAR
    SEL_751_1_SEL.FO_RB_RB02.operClear.ctlVal := FALSE;
    SEL_387E_1_SEL.FO_RB_RB1.operSet.ctlVal := TRUE;            //Set RB1 for SEL-387E to open CB1-2 (Backup for CB1)
    SEL_387E_1_SEL.FO_RB_RB1.operClear.ctlVal := FALSE;
    SEL_421_1_SEL.FO_RB_RB1.operSet.ctlVal := TRUE;             //Set RB1 for SEL-421 to open CB1
    SEL_421_1_SEL.FO_RB_RB1.operClear.ctlVal := FALSE;
    SEL_700G_1_SEL.FO_RB_RB2.operSet.ctlVal := TRUE;            //Set RB2 for SEL-700G_1 to open CB-G1
    SEL_700G_1_SEL.FO_RB_RB2.operClear.ctlVal := FALSE;
    SEL_700G_2_SEL.FO_RB_RB2.operSet.ctlVal := TRUE;            //Set RB2 for SEL-700G_1 to open CB-G2
    SEL_700G_2_SEL.FO_RB_RB2.operClear.ctlVal := FALSE;
    SEL_2505_1_MB.TMB_7.operSet.ctlVal := TRUE;                 //Siren ON
    SEL_2505_1_MB.TMB_7.operClear.ctlVal := FALSE;
    SEL_2505_1_MB.TMB_8.operSet.ctlVal := FALSE;
    SEL_2505_1_MB.TMB_8.operClear.ctlVal := TRUE;
    MICROGRID_HMI.SRBC_00100.operSet.ctlVal := TRUE;            //Microgrid Safe Alarm MA-07 ON
    MICROGRID_HMI.SRBC_00100.operClear.ctlVal := FALSE;
ELSE
    SEL_751_1_SEL.FO_RB_RB02.operSet.ctlVal := FALSE;           //Set RB2 for SEL-751 to open CB-SOLAR
    SEL_751_1_SEL.FO_RB_RB02.operClear.ctlVal := TRUE;
    SEL_387E_1_SEL.FO_RB_RB1.operSet.ctlVal := FALSE;           //Set RB1 for SEL-387E to open CB1-2 (Backup for CB1)
    SEL_387E_1_SEL.FO_RB_RB1.operClear.ctlVal := TRUE;
    SEL_421_1_SEL.FO_RB_RB1.operSet.ctlVal := FALSE;            //Set RB1 for SEL-421 to open CB1
    SEL_421_1_SEL.FO_RB_RB1.operClear.ctlVal := TRUE;
    SEL_700G_1_SEL.FO_RB_RB2.operSet.ctlVal := FALSE;           //Set RB2 for SEL-700G_1 to open CB-G1
    SEL_700G_1_SEL.FO_RB_RB2.operClear.ctlVal := TRUE;
    SEL_700G_2_SEL.FO_RB_RB2.operSet.ctlVal := FALSE;           //Set RB2 for SEL-700G_1 to open CB-G2
    SEL_700G_2_SEL.FO_RB_RB2.operClear.ctlVal := TRUE;
    SEL_2505_1_MB.TMB_7.operSet.ctlVal := FALSE;                //Siren OFF
    SEL_2505_1_MB.TMB_7.operClear.ctlVal := TRUE;
    SEL_2505_1_MB.TMB_8.operSet.ctlVal := TRUE;
    SEL_2505_1_MB.TMB_8.operClear.ctlVal := FALSE;
    MICROGRID_HMI.SRBC_00100.operSet.ctlVal := FALSE;           //Microgrid Safe Alarm MA-07 OFF
    MICROGRID_HMI.SRBC_00100.operClear.ctlVal := TRUE;
END_IF
```

Figure 32. Emergency Safety Shutdown System Code (RTAC)

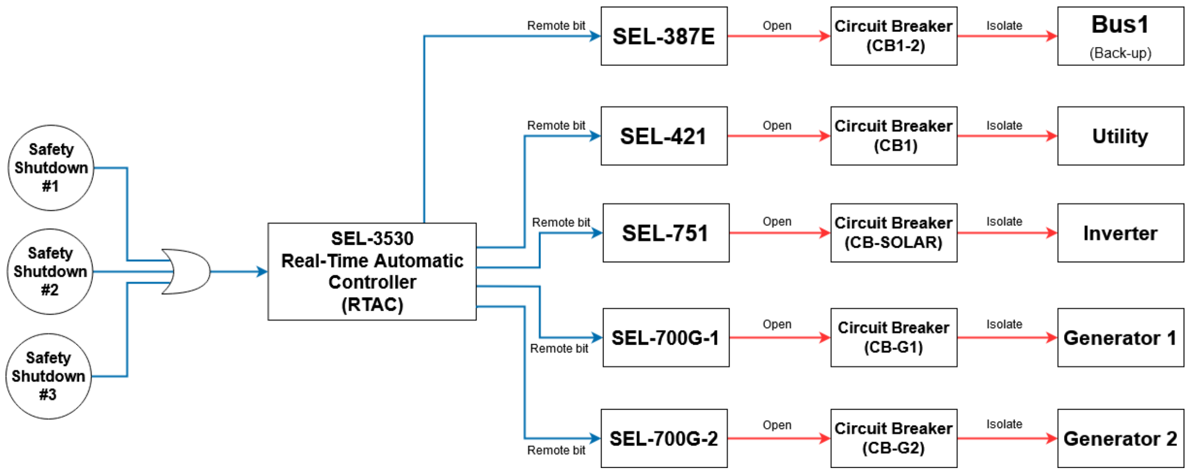


Figure 33. ESS Signal Flow Diagram

The goal is to isolate all power sources, especially the utility bus, which has the most considerable fault contribution. As shown in Figure 33, the SEL-387E will trip CB1-2 as a backup if CB1 fails to trip. In addition to de-energizing the Microgrid, an "Emergency Safety Shutdown" alarm will flash continuously on the annunciator panel, and a dedicated siren, Figure 35, will alarm to draw attention. The siren is controlled by the RTAC using Transmit Mirrored Bits available in the SEL-2505. The SEL-2505's contact OUT7 (NO) and OUT8 (NC) are connected to the Schneider Electric contactor to control the siren, Figure 34. A designated cut-out is connected in series to isolate the siren manually for maintenance and testing purposes. The annunciator and siren will only be defeated once the triggered ESS switch is turned off. This permissive logic ensures the ESS system would be re-armed for future use. Chapter 6.3 contains the ESS system test and results.

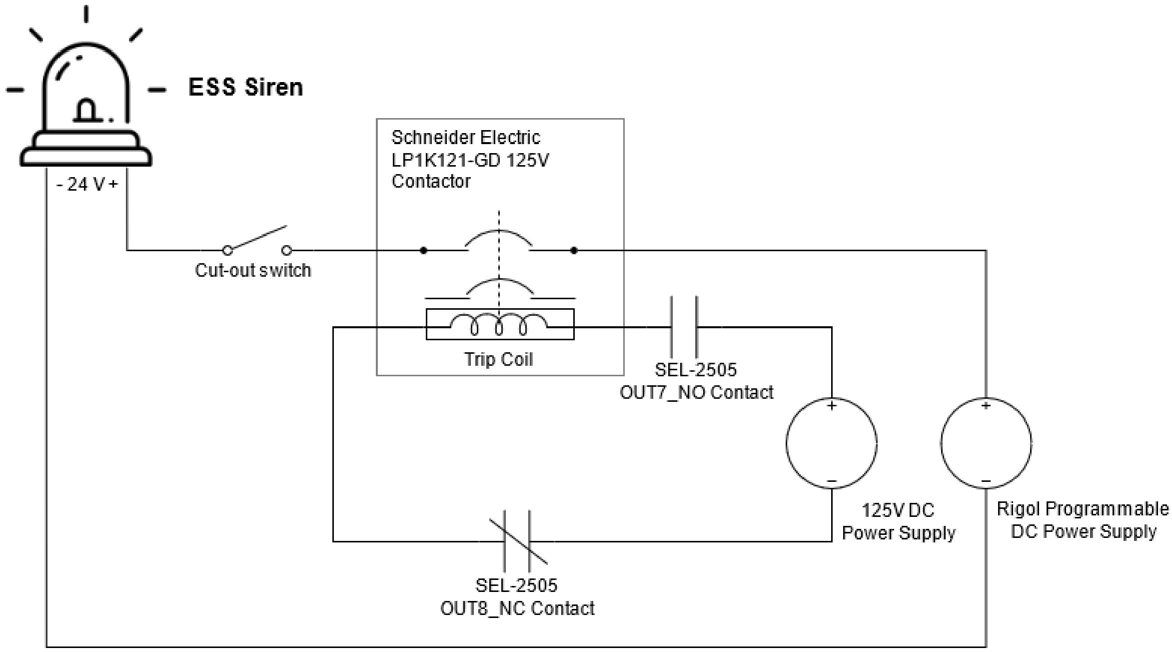


Figure 34. ESS Siren Schematic

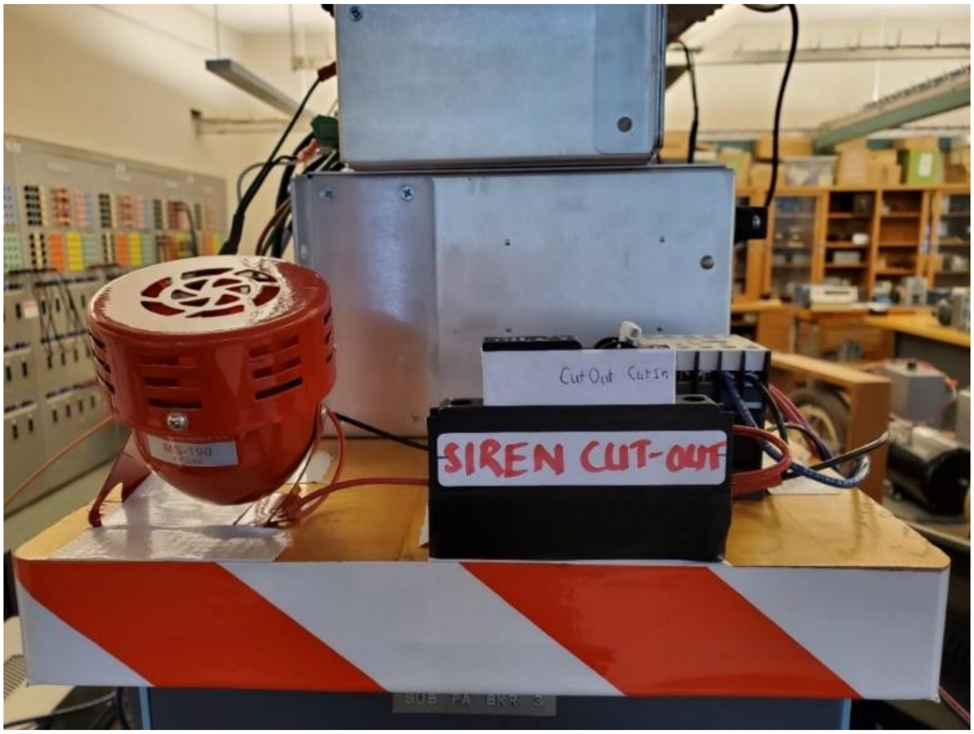


Figure 35. ESS Siren, Cut-out Switch, and Circuit Breaker

6.3 ESS SYSTEM TEST

All three switches were tested one by one to ensure each switch actuation can safely and quickly de-energize the Microgrid, Figure 36. The test verified that any one of the switches could trip the following circuit breakers: CB1, CB1-2, CB-SOLAR, CB-G1, and CBG2 and activated the siren. Figure 37 shows a sample event report file from the SEL-421. The RTAC transmits the remote bit RB-01 to the SEL-421 once the ESS switched is activated. This report captured the current and voltage waveforms before and after remote bit RB-01 asserted. The current diminished once RB-01 and the trip logic became true, thus tripping CB1.

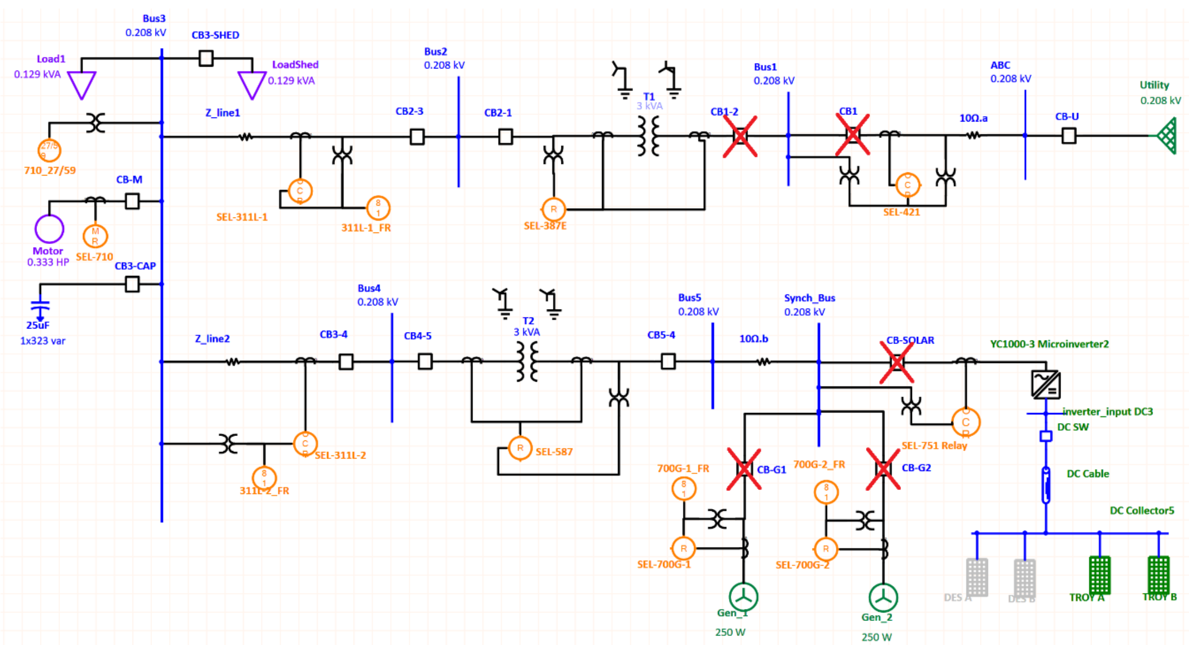


Figure 36. ESS Isolation Points (ETAP software)

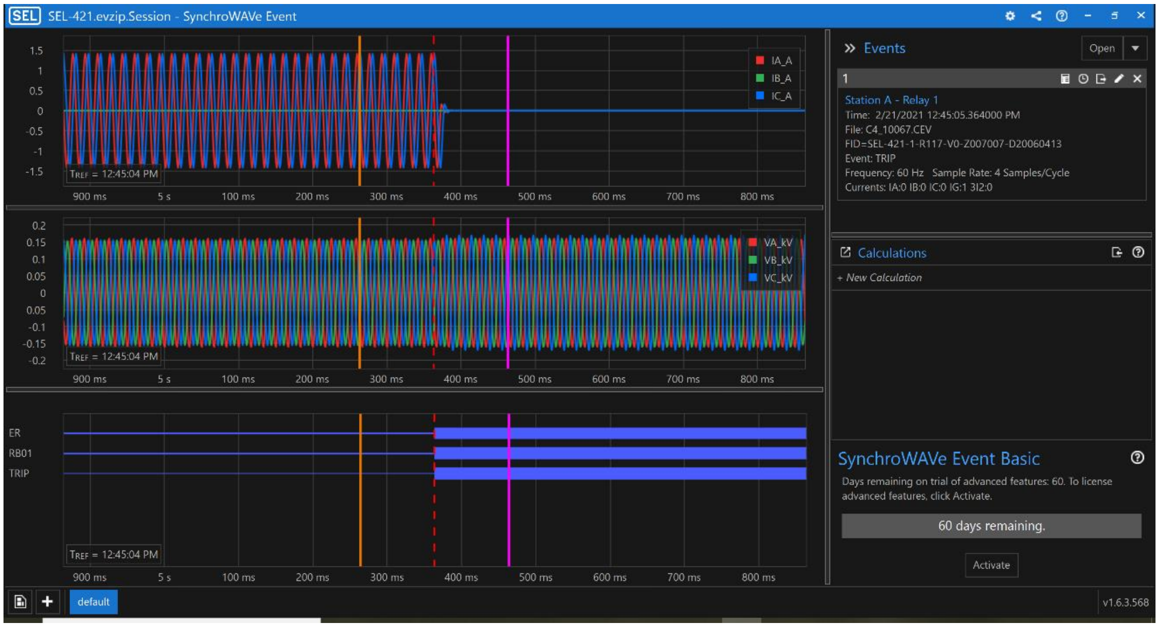


Figure 37. SEL-421 Waveform for CB1 when the ESS activated (SynchroWAVe)

CHAPTER 7. WILDFIRE RISK MITIGATION

This chapter provides background information on California wildfires. Various strategies developed across the utility industry to battle the ongoing threat of extreme weather conditions and the risk of out-of-control wildfires. Such strategies consist of risk management, risk reduction, and risk elimination. This chapter focuses on the risk reduction strategy by dynamically changing protective relay settings to mitigate wildfire risk.

7.1 CALIFORNIA WILDFIRES

In 2017 and 2018, California experienced the deadliest and most destructive wildfires in its history. Fueled by drought, an unprecedented buildup of dry vegetation, and extreme winds, these wildfires' size and intensity caused the loss of more than 100 lives, destroyed thousands of homes, and exposed millions of urban and rural Californians to unhealthy air. While climate change is considered a key driver of this trend, the electric power system has become vulnerable to spark fires when challenged by extreme winds and low humidity. From the California Public Utility Commission's (CPUC) 2014 to 2016 Fire Incident Data Collection, a total of 1,384 individual fire incidents have been reported by electric utilities [8].

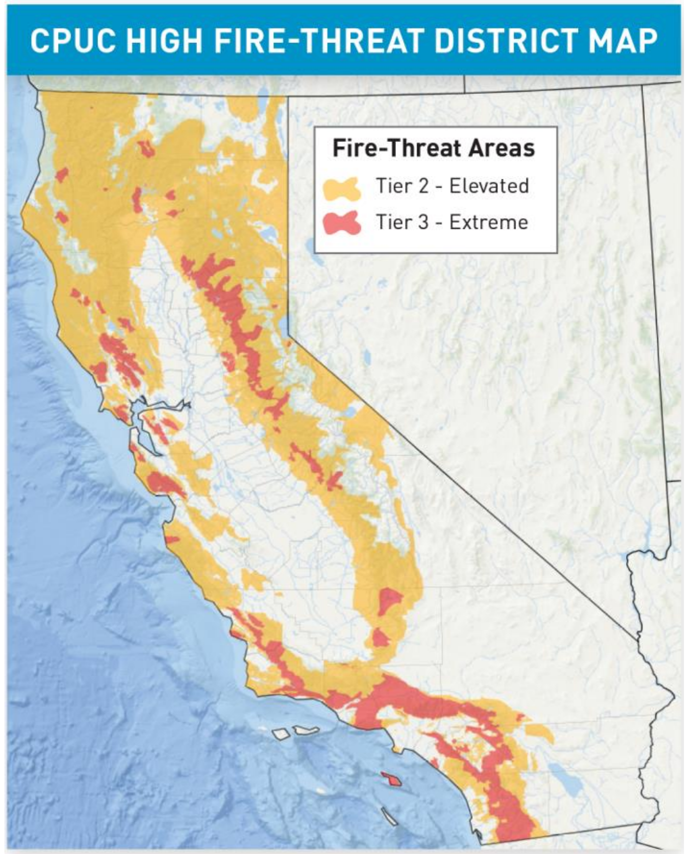


Figure 38. CPUC High Threat Fire Map (January 2019)

Californian utilities such as Pacific Gas and Electric (PG&E) will consider de-energizing distribution and transmission lines passing through areas that the California Public Utilities Commissions have designated as elevated risk (Tier 2) or extreme risk (Tier 3) for wildfires. Customers who do not live or work in an impacted area may find power shut off if their communities rely upon a power line passing through an area experiencing extreme fire danger conditions [9].

7.2 WILDFIRE MITIGATION

Wildfire risks can be mitigated by various strategies, such as risk management, risk reduction, and risk elimination. Risk management primarily involves infrastructure improvement while risk reduction deploys protective relay settings. Risk elimination is the last resort to eliminate wildfire risk potentially sparked by power equipment, namely Public Power Safety Shutoff (PSPS), by de-energizing distribution and transmission lines that pass through high fire-threat areas. The following strategies are proposed in the Grid Safety and Resiliency Program (GS&RP) that aligns with the wildfire mitigation plans required by Senate Bill 901 by Southern California Edison (SCE) [10].

Risk management includes but is not limited to the installation of the following components:

- Insulated Wires: to prevent ignition caused when objects such as metallic balloons, tree limbs, and palm fronds come in contact with the power line.
- Current Limiting Fuses: to interrupt current more quickly and sectionalize the affected areas.
- High-Definition Camera: to enable emergency management personnel and fire agencies to respond more quickly to spreading wildfires.
- Weather Station and Modelling Tools: to increase situational awareness, support operational decision making and resource allocation.
- Vegetation Management: to prevent trees from striking electrical equipment, especially during extreme wind conditions.

Risk reduction:

- Remote-Controlled Automatic Reclosers (RARs): typically used to reenergize the circuit following a self-recovered faulted condition quickly. During Red Flag conditions (low humidity and high wind), the RARs' automatic re-energization function will be disabled, allowing a safely de-energized line for physical crew inspection.

- Protective Relay Settings: various protective group settings can be remotely or locally switched in to better protect the circuit during Red Flag conditions. More conservative group settings such as instantaneous elements would be prioritized over the time-delayed element. These group settings allow less time for faults to sustain and quickly distinguish the arc or spark.

Risk Elimination

- Public Power Safety Shutoffs: to proactively de-energize sections of the electrical systems under extreme fire conditions to zero out the chances of sparks caused by power lines and protect the public's safety.

7.3 RISK REDUCTION

The Microgrid does not have a practical means to simulate a high wildfire risk condition nor actual high wildfire risk potential. However, as a proof of concept, the SEL-751 will have a second group setting designated the risk reduction strategy. This group setting contains the all the protection elements such as overcurrent, undervoltage, and underfrequency. The pick-up values for each element and time delay are reduced to increase sensitivity and speed when a presumably abnormal grid event is detected. To simulate a high wildfire risk signal, the Rigol programmable power supply is used to provide a 24 VDC control signal to the SEL-2505 Remote I/O Module. The SEL-2505 transmits the control signal to SEL-3530 RTAC via the serial port. Upon receiving the trigger signal, the RTAC will send a remote bit to the SEL-751 to change its group setting.

CHAPTER 8. MICROGRID OPERATING PROCEDURE

The Microgrid Operating Procedure (MOP) is designed to fully test and evaluate the Microgrid performance with the newly added features such as load shedding, annunciator panel, power panel, and emergency safety shutdown system. The secondary goal of the MOP is to standardize major grid operations such as startup, generator synchronization, utility synchronization, and shutdown. Following the step-by-step instruction of the MOP ensures the students (operators) can safely experiment the Microgrid and maintain a hazard free work environment. Additional placekeeping technique and various tips and tricks from past operating experience are shared in the discussion section and notes throughout the procedure to successfully operate the Microgrid. The procedure was tested by author and another electrical engineering student with little knowledge of the Microgrid to ensure readability and executability. The MOP is detailed in Appendix B.

CHAPTER 9. CONCLUSION

All engineering designs were carefully tested and evaluated against the design requirements and specifications set forth in Chapter 3 using the Microgrid Operating Procedure, see Appendix KK. All tests were performed under the thesis advisor's supervision and strictly followed all Covid-19 guidance from the university.

The automation design proved to have met all the requirements. The SEL relays and the SEL-3530 RTAC communicated bidirectionally with no errors. The load shedding scheme worked as expected to stabilize the Microgrid from frequency instability following power decline events from the solar panels. The RTAC successfully changed the SEL-751 relay group setting following a 24 VDC command signal from the Rigol power supply via the SEL-2505. Grid parameters such as voltage, current, frequency, real power, reactive power, breaker status, generator status, etc., from the SEL relays, were closely monitored via the SEL aSELerator RTAC software and verified accuracy against the Yokogawa three-phase power meters on bench #5 and bench #6. The annunciator panel displayed accurate alarms as designed following normal and abnormal grid conditions. The annunciators proved to provide a great visual aid in operating the Microgrid. The meter panel provided reliable voltage, real power, reactive power, and frequency data of the generating units and the building grid to support operators that would otherwise be relied upon from the Yokogawa. Finally, the ESS switches safely de-energized and isolated the Microgrid by simultaneously tripping circuit breakers CB-G1, CB-G2, CB-SOLAR, CB-1-2, and CB1 with no time delay or misoperation. The siren was immediately triggered to provide an audible alert following the ESS actuation.

CHAPTER 10. DIFFICULTIES ENCOUNTERED

Difficulties encountered throughout this project are related to the equipment and the Covid-19 pandemic. Such difficulties required troubleshooting, research, rescheduling, and additional testing to meet design requirements and specifications. This chapter highlights major difficulties that significantly impacted the pace of the project. Difficulties encountered throughout the design and implementation process enabled the opportunity for learning and further understanding of the equipment.

10. 1 EQUIPMENT

Equipment difficulties were due to unfamiliarity with the SEL-3530 RTAC, SEL-2505, and other SEL relays. Unlike typical SEL relays that can be set using the SEL aSELerator Quickset software, the RTAC, as a microprocessor-based controller, uses aSELerator RTAC SEL-5033 software. The SEL-5033 software has a completely different user interface, features, and coding requirements that demand timely research to familiarize. To communicate bidirectionally with the RTAC, the SEL device must be connected to one of the RTAC's rear ports. All communication parameters for the associated port must match with the existing parameters of the device to be connected (Baud Date, Data Bits, Parity Bits, Accept Receive Identification, Send Transmit Identification). For example, the SEL-2505's control switches 1 to 10 are used to set up communication for the front port. The RX_ADD (switches 4 and 3) and TX_ADD (switches 2 and 1) numerical value need to match with the RTAC's Send Transmit Identification and Accept Receive Identification, respectively, see Figure 39. The initial attempt had the above parameters configured backward and, therefore, could not establish a successful connection.

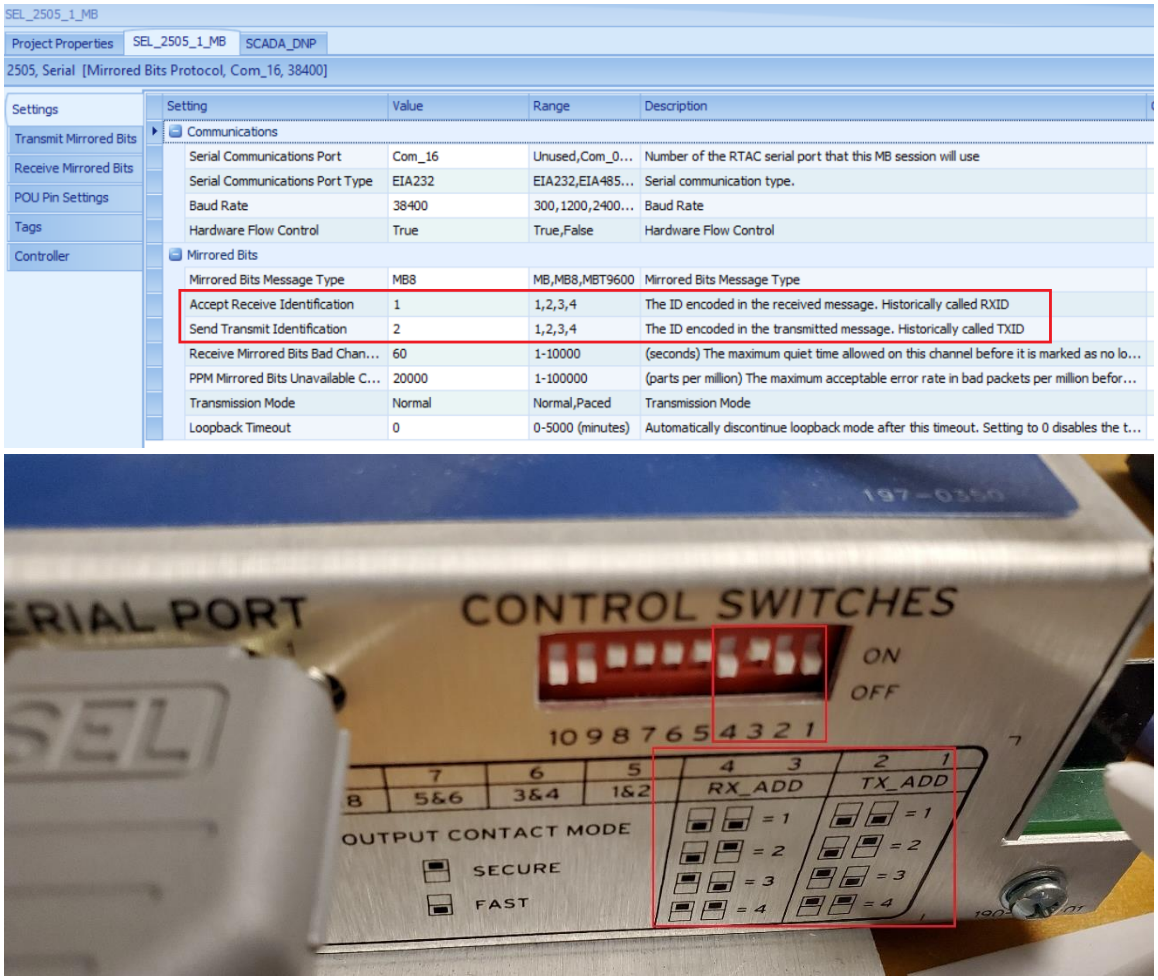


Figure 39. SEL-2505 RTAC Setting (Top) - SEL-2505 Control Switches (Bottom)

A communication issue between the SEL-751 and RTAC arose when switching group settings within the relay. Under a newly written logic reserved for future wildfire risk reduction, the SEL-751 will change group setting upon receipt of the signal from the Rigol and remote bit command from the RTAC. Multiple unsuccessful attempts to troubleshoot from the RTAC led to suspicion in the communication setting of the relay. Further research into the instruction manual revealed that SEL Fast Operate, Figure 40, must be turned on to enable the SEL-751 to receive binary control commands from the RTAC. The relay successfully changed the group setting after implementing the Fast Operate protocol.

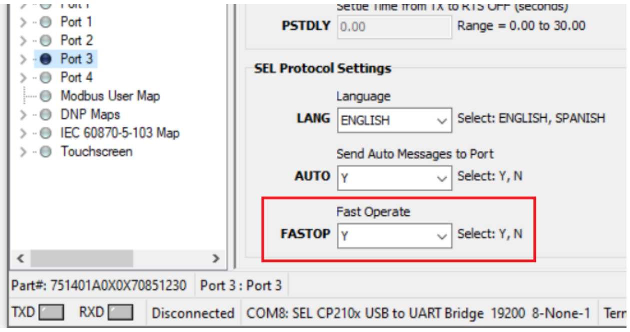


Figure 40. SEL-751 Port Setting (aSELerator Quickset)

Another difficulty encountered when designing the annunciators for the static load status or load shed (MA-05) and the inverter synchronization process (MB-04); see Appendix B for annunciator tags. Unlike the generating units, which have a designated relay to monitor the voltage, current, and power, the static load used for load shedding has no relay assigned or potential signal upstream and downstream of the circuit breaker to monitor the status, Figure 5. The trip signal to CB3-SHED from the SEL-311L can be used as a triggering signal for the annunciator; however, the annunciator might give a false indication if the breaker fails to close or open. The optimal solution is to install a potential downstream of the breaker such that if the 120V L-N is present, then the circuit breaker must have been closed and the load has been online. The challenge surfaced when looking for an SEL relay to feed the potential wire to as all existing relays' potential slots have been used. Further research identified port IN101 (Figure 41) of the RTAC can accommodate a potential wire. This setup failed to give the correct status of the static load. Additional troubleshooting revealed that since AC voltage is a sine wave, the signal will get picked up and dropped out every cycle. This finding necessitated appropriate pick-up levels and delays at the RTAC Contact I/O setting to account for the 60 Hz waveform when using IN101 to detect 120 VAC signals such that all instantaneous signals less the pick-up level will get filtered out between cycles. Figure 42 details the final setting for input IN101 per vendor recommendation.

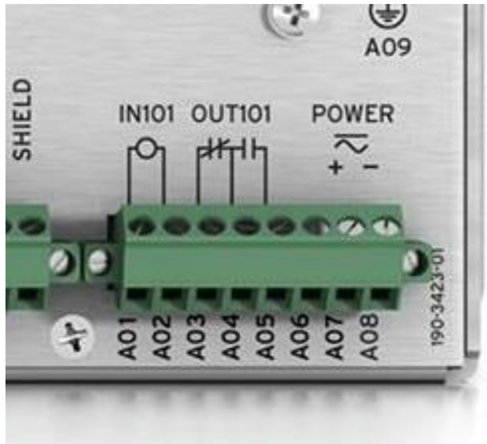
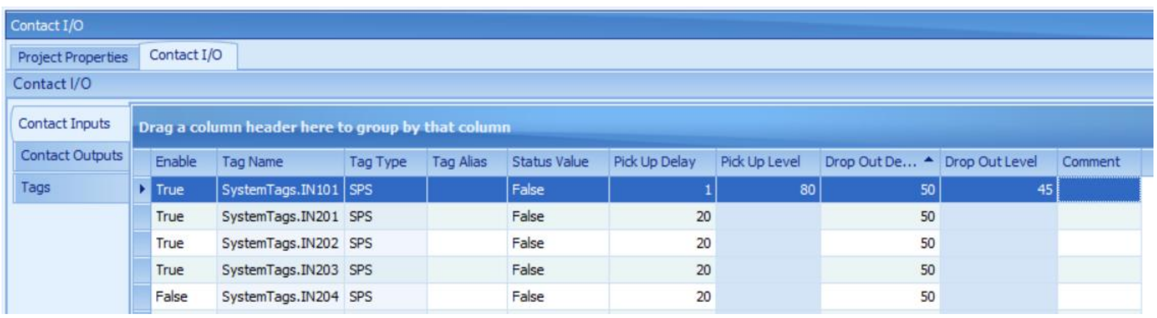


Figure 41. RTAC IN101 Slot



Enable	Tag Name	Tag Type	Tag Alias	Status Value	Pick Up Delay	Pick Up Level	Drop Out De...	Drop Out Level	Comment
True	SystemTags.IN101	SPS		False	1	80	50	45	
True	SystemTags.IN201	SPS		False	20		50		
True	SystemTags.IN202	SPS		False	20		50		
True	SystemTags.IN203	SPS		False	20		50		
False	SystemTags.IN204	SPS		False	20		50		

Figure 42. RTAC IN101 Setting (SEL-5033 Software)

Lastly, the APsystem microinverter typically draws about 1 W from the grid following CB-SOLAR closure. This power flow led to a negative wattage value seen by the SEL-751. The associated annunciator algorithm in the RTAC is written such that any power value less than 0 from the SEL-751 will trigger inverter synchronization status annunciator (MB-04). First attempts were not successful in tracking the synchronization process of the microinverter. Further troubleshoot identified the SEL-751 is not designed to pick up such a small wattage value, and therefore could not transmit the correct value to the RTAC. The decision was made to use the SEL-735 Power Quality Meter’s power signal, which offers higher resolution and sensitivity, in place of the SEL-751's to feed the RTAC. The annunciator worked as designed following this implementation.

10. 2 THE COVID-19 PANDEMIC

Access to laboratory room 101 and room 102 was restricted due to the stay-at-home order at the beginning of the pandemic. This access restriction stalled the implementation, testing, and troubleshooting phases of the project for approximately two quarters. Fortunately, as more Centers for Disease Control and Prevention (CDC) and state guidance about Covid-19 became available, limited campus access starting in the Fall 2020 enabled hardware and software implementation.

Additional precautionary quarantine time of the student and thesis advisor led to multiple cancellations of the scheduled work. However, with guidance and support from the thesis advisor, flexible work hours during weekends expedite the project's pace. Lastly, experimentation in the lab room strictly followed the university's safety guidelines, such as 6-ft social distancing, masking mandate, gloves, and sanitization.

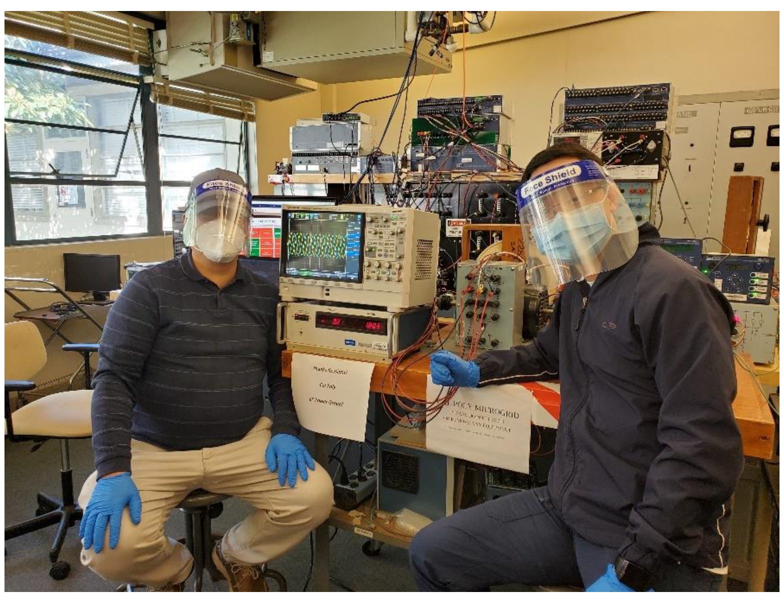


Figure 43. Lab Work during the Covid-19 Pandemic

CHAPTER 11. RECOMMENDED FUTURE WORK

Although many features were added over the years to improve and diversify the Microgrid, there remain areas for improvement. This chapter offers recommendations for future projects to further enhance the Microgrid based on the past operating experience. Besides, this chapter references regulatory standards and requirements set forth by the Federal Energy Regulatory Commission (FERC) and the North American Electric Reliability Corporation (NERC) that utilities in the United States abide by unless exempted. FERC is an independent government agency that regulates the interstate transmission of electricity, natural gas, and oil. NERC, subject to FERC's oversight, is a not-for-profit international regulatory authority whose mission is to ensure the reliability and security of the grid. For example, utilities operating in California such as Pacific Gas and Electric (PG&E), San Diego Gas and Electric (SDG&E), and Sacramento Municipal Utility District (SMUD) are subject to the Western Electricity Coordinating Council (WECC) oversight as an approved Regional Entity that enforces NERC's Reliability Standards as well as FERC's orders. The Microgrid, being a laboratory electrical system not connected to the Bulk Electric System (BES), is not subject to the above regulatory agencies. However, future projects should make every effort to reflect and recognize the existing regulatory requirements wherever possible.

11.1 MULTI-STEP LOAD SHEDDING

The existing resistive load contains six 1000 Ω resistors connected in parallel. Each resistor is paralleled using a manual switch. The RTAC load sheds by opening CB3-SHED to isolate all six resistors (~166.67 Ω). This load reduction amounts to ~250 W, approximately 1/3 of the Microgrid's total load. 30% instant load shedding is not practical in the industry as such load reduction may further destabilize the grid by inducing potential overfrequency excursions. The load shedding test in Chapter 4.5 verified this condition. It is a standard industry practice to shed load equivalent to about 10% of demand using a multi-step load shedding scheme. Each load shedding step initiates based on various underfrequency thresholds. At the Microgrid, a multi-step load shedding scheme can be achieved by replacing manual switches on the resistor box with circuit breakers controllable by the RTAC or SEL relays. Efforts should be made in the design process to reflect NERC Standard PRC-006-3. This regulatory standard establishes design requirements for automatic underfrequency load shedding programs to arrest declining frequency [11].

11.2 AUTOMATIC VOLTAGE REGULATOR

The electrical grid is inherently dynamic. Grid voltage and frequency vary as load demand and power generation fluctuate. A grid-tied generator requires an automatic voltage regulator (AVR) to stabilize the generator terminal voltage. Such well-maintained voltage control is critical to the overall stability of the grid. As such, NERC Standard VAR-002-4.1 "Generator Operation for Maintaining Network Voltage Schedules" requires Generator Operator whose generator is connected to the interconnected transmission system to operate in the automatic voltage control mode with the VAR in service [12]. At the Microgrid, the lack of an AVR requires continuous attention and manual tuning of the generator to maintain appropriate voltage level during all modes of operation. Such manual voltage control is impractical and inefficient. An automatic voltage regulator can be achieved by installing a control system that automatically adjusts the field current supply based on the generator's terminal voltage feedback loop.

11.3 GOVERNOR CONTROL

Significant power deficiency or large grid disturbance can lead to frequency deviations, thus destabilize the network. The governor/turbine control of grid-tied generators plays a critical role in maintaining a dynamic electrical grid's overall stability. The microgrids with inherently less rotating mass and power reserve are more prone to such frequency variation. FERC requires any new synchronous and nonsynchronous generators to install, maintain, and operate equipment capable of providing Primary Frequency Response (PFR) as an interconnection condition. PFR action begins within seconds after system frequency deviation and is provided by the turbine-governor control's automatic and autonomous actions. Such actions aim to arrest abnormal frequency variations and maintain the system frequency within acceptable bounds [14]. NERC, subject to oversight by the FERC, recommends all generating resources be equipped with a functioning governor and governor control setting [15]. The Microgrid should recognize these regulatory requirements for generators that affect the utility industry. A practical governor control can be achieved by designing a control system that adjusts the DC motor's (acting governor of the existing generator) speed based on the generator frequency feedback loop.

11.4 WIND TURBINE

The amount of wind electricity generation in the United States has expanded quickly in the past 30 years. The total annual electricity generation from wind energy increased from 6 billion kWh in 2000 to about 300 billion kWh in 2019 [16]. As such, wind electricity has become an integral part of a modern electric grid. A wind turbine should be added to the Microgrid as another power source to replicate a modern grid and diversify power generation sources. Such installation enhances the dynamic characteristic of the system and provides a great learning opportunity for the students.

11.5 SOLAR ARRAY SIMULATOR

The existing solar panel's hour of operation relies entirely on the weather and the time of the day. The aisle between building 20A and room 20-102, where the solar car stations, is only unshaded for 4 to 5 hours a day, depending on the season. This limited availability poses a significant challenge to operate the Microgrid at total capacity. Complete dependence on the weather creates a realistic but uncontrollable environment; thus, power generation proves to be impractical for experimental purposes. The presence of a solar panel cart also blocks the walkway and can become hazardous for walkers. As such, a DC power supply equipped with a solar array simulator software is recommended to replace the solar panels to provide a controllable test environment and complete availability to power the APsystem microinverter. Recommended solar array simulators for consideration are Keysight E4360 and BK Precision PVS1005/PVS60085.

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APPENDIX A – ANNUNCIATOR AND METER PANEL DATA

Table 8. Annunciator Information

Annunciator ID	Destination Tag SCADA_MAP_DNP.	Source Tag MIDGROGRID.	Normal State	Alarm State
MA-01	BI_00085	SRBC_0085	INFINITE BUS FREQUENCY NORMAL	INFINITE BUS FREQUENCY NORMAL
MB-01	BI_00086	SRBC_0086	INFINITE BUS VOLTAGE NORMAL	INFINITE BUS UNDER VOLTAGE
MC-01	BI_00087	SRBC_0087	POWER FLOW NORMAL	BACK FEEDING
MD-01	BI_00088	SRBC_0088	VAR SUPPORT NORMAL	VAR EXPORT
MA-02	BI_00075	SRBC_0075	GEN #1 FREQUENCY NORMAL	GEN #1 UNDER FREQUENCY
MB-02	BI_00076	SRBC_0076	GEN #1 VOLTAGE NORMAL	GEN #1 UNDER VOLTAGE
MC-02	BI_00077	SRBC_0077	POWER FLOW NORMAL	LOW POWER
MD-02	BI_00078	SRBC_0078	OVEREXCITED	UNDEREXCITED
MA-03	BI_00065	SRBC_0065	GEN #2 FREQUENCY NORMAL	GEN #2 UNDER FREQUENCY

MB-03	BI_00066	SRBC_0066	GEN #2 VOLTAGE NORMAL	GEN #2 UNDER VOLTAGE
MC-03	BI_00067	SRBC_0067	POWER FLOW NORMAL	LOW POWER
MD-03	BI_00068	SRBC_0068	OVEREXCITED	UNDEREXCITED
MA-04	BI_00080	SRBC_0080	INVERTER POWER NORMAL	INVERTER LOW POWER
MB-04	BI_00082	SRBC_0082	SYNCHRONIZATI-ON IN PROGRESS	SYNCHRONIZAT-ION PROCESS NOT ACTIVATED
MC-04	BI_00083	SRBC_0083	RESERVED	RESERVED
MD-04	BI_00084	SRBC_0084	RESERVED	RESERVED
MA-05	BI_00095	SRBC_0095	STATIC LOAD CONNECTED	LOAD SHED
MB-05	BI_00096	SRBC_0096	CAP BANK CONNECTED	CAP BANK DISCONNTED
MC-05	BI_00097	SRBC_0097	PUMP CONNECTED	PUMP DISCONNECTED
MD-05	BI_00098	SRBC_0098	RESERVED	RESERVED

MA-06	BI_00089	SRBC_0089	GRID-TIED	ISLANDED MODE
MB-06	BI_00079	SRBC_0079	GEN #1 SYNCHED	GEN #1 ISOLATED
MC-06	BI_00069	SRBC_0069	GEN #2 SYNCHED	GEN #2 ISOLATED
MD-06	BI_00081	SRBC_0081	INVERTER SYNCHED	INVERTER ISOLATED
MA-07	BI_00100	SRBC_00100	MICROGRID SAFE	EMERGENCY SAFETY SHUTDOWN
MB-07	BI_00101	SRBC_00101	WEATHER NORMAL	HIGH FIRE RISK
MC-07	BI_00102	SRBC_00102	ISLANDING SAFE	ISLANDING ABORT
MD-07	BI_00103	SRBC_00103	SAFE POWER MARGIN	INSUFFICIENT POWER/ FREQ UNSTABLE

Table 9. Meter Panel Information

	Category	Tag Name
UTILITY	Voltage	SCADA_MAP_DNP.AI_00143
	Power	SEL_421_1_SEL.FM_INST_P_WATTS
	VAR	SEL_421_1_SEL.FM_INST_Q_VARS
GEN #1	Voltage	SEL_700G_1_SEL.FM_INST_VAX
	Power	SEL_700G_1_SEL.FM_INST_P3X
	VAR	SEL_700G_1_SEL.FM_INST_Q3X
GEN #2	Voltage	SEL_700G_2_SEL.FM_INST_VAX
	Power	SEL_700G_2_SEL.FM_INST_P3X
	VAR	SEL_700G_2_SEL.FM_INST_Q3X
INVR.	Voltage	SCADA_MAP_DNP.AI_00144
	Power	SEL_751_1_SEL.FM_INST_P
	VAR	SEL_751_1_SEL.FM_INST_Q
PUMP	Voltage	SEL_710_1_SEL.FM_INST_VA
	Power	SEL_710_1_SEL.FM_INST_P
	VAR	SEL_710_1_SEL.FM_INST_Q
FREQ_1	Frequency (Hz)	SEL_700G_1_SEL.FM_INST_FREQX
	Speed (RPM)	SCADA_MAP_DNP.AI_00141

FREQ_2	Frequency (Hz)	SEL_700G_2_SEL.FM_INST_FREQX
	Speed (RPM)	SCADA_MAP_DNP.AI_00142
GEN_TOTAL	Sum of all sources	SCADA_MAP_DNP.AI_00140
Reserved	Volt	No tag assigned
	Power	No tag assigned
	VAR	No tag assigned

APPENDIX B – MICROGRID OPERATING PROCEDURE

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Microgrid Operating Procedure

06/12/2021
Effective Date

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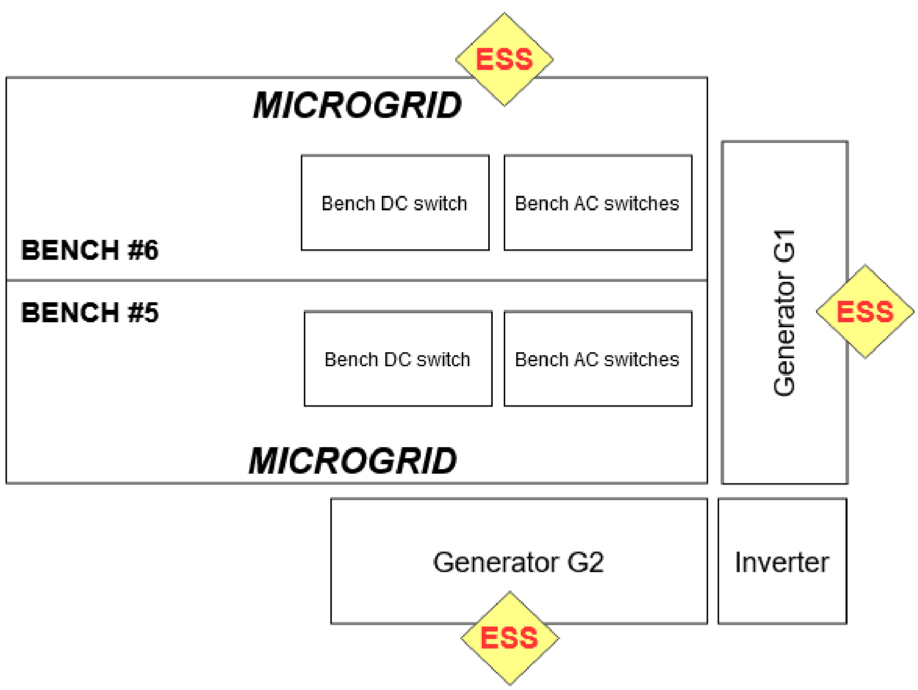
STOP WORK immediately, **PRESS** the Emergency Safety Shutdown (ESS) switch, and **REPORT** to the EE department faculties of the microgrid's suspicious behaviors that include, but are not limited to, loud, inconsistent noise, shaking from the generator, DC motor, smoke, arcing, corona, and equipment damage. The ESS switches are located at the generator carts, and bench 6 marked with red-yellow tape. Everyone has the right to stop work amid safety concern.

In case of emergency, **DIAL 911.**



ESS Switches Location

1. SCOPE

1.1 This procedure provides instructions to safely operate the Microgrid during the startup, grid-connected, and islanded mode of operation.

1.2 This procedure provides instructions to test the load shedding scheme.

2. DISCUSSION

2.1 The Microgrid consists of two synchronous generators (500W each) and a microinverter connected to pair of solar panels (210W combined) as the generating units. The two generators provide base load with voltage and frequency support to the grid when operating in the islanded mode. The microinverter provides additional power during the daytime. The grid can be connected to the building grid (utility) to provide initial system synchronization and to support the grid when the generator(s) becomes unavailable.

2.2 The main protection system includes two SEL-700G Generator Protection Relays to protect the generators, one SEL-751 Feeder Protection Relay to guard microinverter branch, and one SEL-421 Protection Automation Control to protect the utility connection. Working in conjunction with above relays are SEL-587 Current Differential Relay, SEL-311L Line Current Differential Protection and Automation, and SEL-710 Motor Protection Relay to protect various parts of the Microgrid. All SEL equipment are connected to the SEL-3530 Real-Time Automation Controller (RTAC) to enable efficiency communication and smart automation service to the grid.

2.3 Meter and annunciation are displayed in real-time on the annunciator LCD panel located on bench 5 via the SEL-3530 RTAC. Refer to the main annunciator response procedure MAR to troubleshoot the annunciator. Additional Yokogawa three-phase power meters located on bench 5 and bench 6 can be also be used to meter.

3. DEFINITION

3.1 The Microgrid: The 120/208V smart laboratory electrical system capable of operating independently without the support of the infinite bus.

3.2 SEL: Schweitzer Engineering Laboratories, a manufacturer of digital protects and systems that protect, automate, and control power systems. The Microgrid employs SEL relays to protect critical components and automate various processes.

3.3 ESS: The Emergency Safety Shutdown system designed to safely and promptly deenergize the Microgrid. There are three switches located at the side of the generator carts and bench six. All switches are marked by red-yellow tape. Each switch can shut down the Microgrid.

3.4 Operator: Any individual operates the Microgrid at the time this procedure is being referenced.

4. RESPONSIBILITIES

4.1 The supervising faculty is responsible to ensure that all students working with the Microgrid equipment are aware of the safety features in place to protect against abnormal and unsafe conditions. Safety features include but are not limited to the ESS switches, power cutoff switch, AC and DC switches. The advising faculty must ensure the students have sufficient knowledge to run equipment and work in pair when the Microgrid is energized. The advising faculty shall address to the students of the "Stop Work Authority".

4.2 The student is responsible to obtain the supervising faculty's permission prior to operate the Microgrid. The permission may be effective for an agreed period between the faculty and the student. The student is responsible to work in a pair when the Microgrid is energized. Effort should be made to maintain housekeeping and report any hazardous or unsafe conditions to the supervising faculty.

4.3 All students and faculties are responsible to follow campus coronavirus safety protocols and obey all postings.

5. REFERENCES

<u>NOTE:</u> All reference documents are stored electronically in the Microgrid OneDrive. Contact the supervising faculty for access.

5.1 Grid-tied Solar System by Virginia Yan

5.2 Microgrid Renewable Energy Integration by Do Vo

5.3 Microgrid Lab – Capacitor Bank by Nicole Rexwinkel & Joshua Cinco

5.4 Protection, Automation, And Frequency Stability Analysis of a Laboratory Microgrid System by Eric Osborn

5.5 Protective Relaying Student Laboratory by Kenan Pretzer

6. PREREQUISITES

None.

7. PRECAUTIONS AND LIMITATIONS

7.1 The Microgrid must be operated by two qualified individuals. The operators shall notify the supervising faculty prior to commencing work. Work log shall be properly signed in and dated. Failure to adhere to this requirement will result in a revoke of access.

7.2 A proper walkdown to verify the integrity of the Microgrid must be performed thoroughly before and after each shift. The walkdown shall include, but not limited to, inspecting for looseness, debris, sign of arcing, burnt mark, and equipment misplacement. Rigorous inspection shall be performed at the ESSS switches and siren. Any finding shall be reported to the supervising faculty. DO NOT ATTEMPT TO REMOVE ANY WIRE WHEN THE SYSTEM IS ENERGIZED.

7.3 All windows are to be and remain opened a soon as Room 102 is occupied to ensure maximum air flow. Mask wearing and social distancing practice must be enforced per university requirements. More Coronavirus Information can be found at:

https://coronavirus.calpoly.edu/campus-updates

7.4 Building grid (Building 22 - Engineering East) voltage varies depending on campus load at the time. Annunciator MB-01 monitoring the infinite bus voltage might alarm to alert such grid condition. The Microgrid has been observed to operate with no issue with building grid voltage as low as 116 V L-N without the Microgrid’s load.

8. INSTRUCTIONS

NOTE: Placekeeping is the recommended human performance tool to reduce human errors and prevent the omission or duplication of steps. Refer to Attachment 3 for a proper placekeeping technique demonstration.

NOTE: Visit campus Coronavirus Information to stay up to date with the university requirements. Conservative decision to wear a mask and maintain a 6ft distance shall be taken when uncertain. All university or department postings must be obeyed at all time.

8.1 Preparation

8.1.1 Permission

Obtain approval from the supervising faculty to operate the Microgrid.

Faculty Name: ____________________

Faculty Signature: ____________________ Date: ____________________

Approval Effective From: ____________________ Until:
____

Once approved, this approval sheet can be kept separately for future use.

8.1.2 Walkdown

NOTE: Prior to conducting the walkdown, ensure the Microgrid is de-energized by switching off (downward) switch #5 and switch #6 at the power lab control panel. If no other lab benches in Room 102 are in operation, press the red emergency button for a complete isolation. See Attachment 1, Figure 1 for Room 102 layout.

a. Visually inspect for debris, sign of burnt mark, broken cable, and connection integrity.

b. Physically check for tightness at the terminals of the generators, motor, resistive boxes, and ADF connection of bench 5 and 6.

c. Ensure the ESS switches and connection are intact.

d. Ensure all blue cable are firmly inserted into to the trip signal slot on the green circuit breakers.

e. Report any findings to the supervising faculty.

8.1.3 Annunciator Setup (Ref. Attachment 2, Figure 8)

a. Turn on the LCD TV on bench 5.

b. Connect the HDMI cable to the bench #5 PC or a personal laptop capable of browsing.

c. Connect the USB A/B cable from the computer to Port F of the SEL-3530 RTAC.

d. Enter the following address to a browser https://172.29.131.1/home.sel

e. Login credential sheet is available beneath the LCD TV

f. Select "Thesis" under the HMI section at the bottom left of the home page.

g. Ensure the following annunciator and meter panel are displayed correctly on the screen. Maximize the display size by zooming in via the browser.

NOTE: Login credential sheet shall not be removed from bench #5 or shared. Notify the supervising faculty to report a loss.

NOTE: It may take up to 3 minutes for the annunciator to fully operational. Do not rely on the annunciator during this period.

8.1.4 Power distribution setup (Ref. Attachment 2, Figure 1, and Figure 2)

At the main distribution panel (Attachment 2, Figure X):

a. Use heavy-duty cables at the corner of Room 102 to connect the 120/208VAC source (light green slots) to the ABC slots #6.

> **NOTE:** All connections shall be made up from load-to-source sequence. All disconnections shall be completed from source-to-load sequence

b. Ensure the 208V-3Ø circuit breaker is switched on (upward) at the AC CONTROL panel.

c. Turn ON the two 120V.DC circuit breakers (upward) and press the black motor button at the 125/250V.DC M-G SET panel to energize the main DC source.

d. Observe the DC meter display ranging from 110 – 130VDC. Notify the supervising faculty if the DC voltage level is out of range.

e. Turn ON the GHI #5, GHI #6, and ABC #6 circuit breakers.

At the power lab control panel (Ref. Attachment 2, Figure 3):

f. Press the white “ON” button on the panel.

g. Switch on (upward) switch #5 and switch #6.

h. Verify that orange lights #5 and #6 illuminate.

8.1.5 Relay/Speedometer Setup (Ref. Attachment 2, Figure 4)

Below the generator #2 cart:

a. Ensure the power strip is turned on

b. Verify the left most SEL-700G relay and Magtrol speedometer power up

Below the generator #1 cart:

c. Ensure the power strip is turned on

d. Verify the SEL-700G, SEL-751, SEL-735s, and Magtrol speedometer power up

8.1.6 Solar Panel Setup (Ref. Attachment 2, Figure 9, Figure 10, and Figure 11)

NOTE: The Microgrid is fully self-sustained with two generators in operation. The contribution of renewable energy via the solar panels and microinverter is optional. It is recommended, however, to connect the microinverter to observe the dynamic power generation characteristic of the Microgrid. The following steps instruct to setup the solar panel cart in preparation to run the microinverter.

NOTE: The solar panel cart reposition requires two people. Do not attempt to move the solar panel cart alone. Ensure the traffic cones are set up to enhance precaution at the walkway in between Room 101/102 and the building 20A before maneuvering the solar panel cart.

At room 102:

a. Arrange the DC transmission cables (red and blue) across from the Microgrid to the nearest window.

b. Unroll the cable and extend to solar panel assembly area

At room 101:

c. Ensure both north side doors are fully opened, and the ramp is fully attached to the stair

d. Slowly move the solar panel cart to the walkway.

e. Face the panels towards the sun to maximize energy harvest.

f. If the solar panels are not expected to connect to the Microgrid within 1 hour, turn the panels away from the sun

g. Connect the DC transmission cables to the solar panel via the MC4 connectors male to female.

h. Ensure the DC disconnect switch beneath the solar panel is OFF.

8.2 Start-up

8.2.1 Grid Energization

a. Turn ON Rigol power supply.

b. Ensure the ESS siren is cut-in.

c. Turn ON the Yokogawa three phase power meters on benches 5 and 6.

d. Turn ON the GHI terminal switches (125V DC power supply) on bench 5 and bench 6. Verify all circuit breakers' green LEDs illuminate.

e. Turn ON the ABC terminal switch CB-U on bench 6. Verify line voltage on bench 6's Yokogawa and utility voltmeter at the meter panel read 205V – 209V.

   Expected annunciator status:
   - MA-01 "INFINITE BUS FREQUENCY NORMAL"
   - MB-01 "INFINITE BUS VOLTAGE NORMAL"

f. Close the following circuit breakers in the correct order: CB1, CB1-2, CB2-1, and CB2-3 on bench 6. Verify circuit breakers closed (red LEDs illuminate).

   Expected annunciator status:
   - MC-01 "POWER FLOW NORMAL"
   - MD-01 "VAR SUPPORT NORMAL"

g. Close circuit breaker CB3-4, CB4-5, and CB5-4 on bench 5. Verify power reading on bench 6's Yokogawa and utility wattmeter read 70W - 80W.

h. Verify line voltage reading on bench 5's Yokogawa (180V – 190V L-L)

8.2.2 Generator Energization

<u>NOTE:</u> Both generators have the same specifications and relay settings. Either unit may be energized first. Energization shall be fully completed before moving onto the other unit. The following steps instruct to energize generator #1 first.

<u>At generator #1 cart:</u>

a. Turn ON the DC starter switch of generator #1.

b. Press the "Start" button on the DC starter #1 to turn on generator #1 (Ref. Attachment 2, Figure 5).

c. IF the DC motor does not start, tune the DC motor knob by a quarter of a revolution counterclockwise (Ref. Attachment 2, Figure 6).

d. Verify generator operational by checking the speed in RPM at the Magtrol speedometer.

e. Observe the initial generator speed on the Magtrol speedometer.

f. If the initial generator speed is > 1900 RPM, slightly tune the DC motor knob counterclockwise to decrease the speed to approximately 1850 RPM.

g. Turn the potentiometer clockwise by a quarter of a revolution to establish stable frequency reading (Ref. Attachment 2, Figure 7).

Expected annunciator status (Ref. Attachment 2, Figure 8):

- MA-02 “GEN #1 UNDERFREQUENCY” if speed < 1795RPM (59.83Hz)
- MA-02 “GEN #1 FREQUENCY NORMAL” otherwise
- MB-02 “GEN #1 UNDERVOLTAGE”
- MC-02 “LOW POWER”
- MB-06 “GEN #1 ISOLATED”

<u>At generator #2 cart:</u>

h. Turn ON the DC starter switch of generator #2.

i. Press the “Start” button on the DC starter #2 to turn on generator #2.

j. IF the DC motor does not start, tune the DC motor knob by a quarter of a revolution counterclockwise.

k. Verify generator operational by checking the speed in RPM at the Magtrol speedometer.

l. Observe the initial generator speed on the Magtrol speedometer.

m. If the initial generator speed is > 1900 RPM, slightly tune the DC motor knob counterclockwise to decrease the speed to approximately 1850 RPM

n. Turn the potentiometer clockwise by a quarter of a revolution to establish stable frequency reading.

Expected annunciator status:

- MA-03 “GEN #2 UNDERFREQUENCY” if speed < 1795RPM (59.83Hz)
- MA-03 “GEN #2 FREQUENCY NORMAL” otherwise
- MB-03 “GEN #2 UNDERVOLTAGE”
- MC-03 “LOW POWER”
- MC-06 “GEN #2 ISOLATED”

8.3 Generator Synchronization

NOTE: Either generator may be synchronized first. Synchronization shall be fully completed before moving onto the other unit. The following steps instruct to energize generator #1 first.

NOTE: Adjusting the generator terminal voltage will impact the frequency and vice versa. Finetuning both terminal voltage and frequency is necessary to ensure a successful synchronization.

8.3.1 Generator #1 Synchronization

At the generator #1 cart:

a. Ensure circuit breakers CB-SHED and CB-M are both OPEN.

b. Turn the potentiometer clockwise to increase terminal voltage to approximately 108V L-N. Voltage reading can be taken at the meter panel or from a separate multimeter connected across the generator terminal voltage.

c. Turn the DC motor knob clockwise or counterclockwise to increase or decrease the speed to 1801 RPM to 1814 RPM.

d. Ensure both voltage and frequency are within synchronizing range stated in step 8.3.1b and 8.3.1c.

e. Verify circuit breaker CB-G1 closed by observing the red light illuminating and generator speed (1799 RPM ~ 1801 RPM).

f. Increase the generator #1's output power by slowly turning the DC motor knob clockwise until ~35W power is observed at the meter panel.

Expected annunciator status:

- MA-02 "GEN #1 FREQUENCY NORMAL"
- MB-02 "GEN #1 UNDER VOLTAGE"
- MC-02 "POWER FLOW NORMAL"
- MB-06 "GEN #1 SYNCHED

NOTE: Do not attempt to increase the generator #1 terminal above 108V L-N after synchronized. This will prevent generator #2 from synchronizing.

8.3.2 Generator #2 Synchronization

At the generator #2 cart:

a. Ensure circuit breakers CB-SHED and CB-M are both OPEN.

b. Turn the potentiometer clockwise to increase terminal voltage to approximately 108V L-N. Voltage reading can be taken at the meter panel or from a separate multimeter connected across the generator terminal voltage.

c. Turn the DC motor knob clockwise or counterclockwise to increase or decrease the speed to 1801 RPM to 1814 RPM.

d. Ensure both voltage and frequency are within synchronizing range stated in step 8.3.2b and 8.3.1c.

e. Verify circuit breaker CB-G1 closed by observing the red light illuminating and generator speed (1799 RPM ~ 1801 RPM).

f. Increase the generator #1's output power by slowly turning the DC motor knob clockwise until ~35W power is observed at the meter panel.

   Expected annunciator status:
   - MA-03 "GEN #2 FREQUENCY NORMAL"
   - MB-03 "GEN #2 UNDER VOLTAGE"
   - MC-03 "POWER FLOW NORMAL"
   - MC-06 "GEN #2 SYNCHED

g. Increase generator #2 output power to approximately 50W. Power reading can be taken at the meter panel.

h. Increase terminal voltage to approximately 115V L-N.

At the generator #1 cart:

i. Increase the generator #1 output power to approximately 50W.

j. Increase generator #1 terminal voltage to approximately 120V L-N. This ensures both generators are providing equal power and reactive power support to the grid.

8.4 Load Connection

8.4.1 Resistive Load Connection

At bench 6:

a. Close circuit breaker CB3-SHED.

b. Turn on all the switches at Load 1 resistive box.

c. Close circuit breaker CB-M.

d. Observe circuit breaker CB3-CAP automatically closes.

Expected annunciator status:

- MA-05 “STATIC LOAD CONNECTED”
- MB-05 “CAP BANK CONNECTED”
- MC-05 “PUMP CONNECTED”

> **NOTE:** Full load addition will sag voltage at the generator terminal voltage.

8.4.2 Voltage and Power Correction

a. Simultaneously increase the both generators’ terminal voltage to achieve 120V L-N.

b. Increase generator output power to approximately 100W each.

8.5 Microinverter Connection

> **NOTE:** The Microgrid is fully self-sustained with two generators in operation. The contribution of renewable energy via the solar panels and microinverter is optional. It is recommended however to connect the microinverter to observe the dynamic power generation characteristic of the Microgrid. The following steps instruct to synchronize the microinverter to the Microgrid after both generators have been paralleled and the Microgrid is grid-tied.

8.5.1 Solar Panel Angle Adjustment

<u>At the solar panel cart</u> (Ref. Attachment 2, Figure 10, and Figure 11):

a. Connect the single axial motor controller alligator clips to a 12V battery. (Red positive, black negative).

b. Press “SET” on the remote to change the controller operation to manual.

c. Press “E →” or “W ←” to tilt the solar panels up and down.

> **NOTE:** Automatic operation of the controller is optional. This mode of operation is suited for maximizing power production. Manual mode of operation is better suited for controlling the output power for a short period.

8.5.2 Microinverter Synchronization

a. Tune the generator terminal voltage to achieve 120V L-N and steady.

At the microinverter cart (Ref. Attachment 2, Figure 4):

b. Connect the DC transmission cables to the microinverter via the MC4 connectors male to female.

c. Turn ON the DC disconnect switch beneath the solar panels.

d. Immediately verify three green light flashing on the left side of the microinverter. Three green light flashes notify a successful microinverter startup.

e. Close circuit breaker CB-SOLAR.

f. Close the disconnect switch on the microinverter cart. The closure of the this switch physically ties the microinverter to the Microgrid and begins the 5-minute synchronization process.

   Expected annunciator status:
   - MA-04 “INVERTER LOW POWER”
   - MB-04 “Synchronization In Progress”
   - MD-06 “INVERTER ISOLATED”

g. After 5 minutes, verify the inverter power at the meter panel.

   Expected annunciator status:
   - MA-04 “INVERTER POWER NORMAL”
   - MB-04 “Synchronization Process Not Activated”
   - MD-06 “INVERTER SYNCHED”

8.6 Islanding Mode Transfer

8.6.1 Preparation

a. Ensure the generator is running stably with no voltage or power fluctuation.

b. Ensure the solar panels are not shaded or to be shaded within the next 10 minutes

c. Verify the microinverter output power does not fluctuate more than 10W in magnitude.

d. Optionally assign a station watcher by any generator cart to monitor the speed

8.6.2 Mode Transfer

> **<u>NOTE:</u>** The solar panels output power varies each day. It is important to tune the generators output power accordingly to obtain 50W to 80W power flow from the utility grid before islanding. This wattage dependence has been verified experimentally to ensure a stable mode transfer.

a. Tune the generators output power to achieve utility power reading of 50W to 80W. The power reading can be taken at bench 6 Yokogawa or at the meter panel.

b. Ensure loading and VAR support are equally shared by two generators. This requires simultaneous finetuning at the DC motor knobs.

c. Once all favorable conditions are achieved:

d. Open CB-U breaker to isolate the Microgrid from the building grid.

> **<u>NOTE:</u>** The voltage will dip upon isolation from the building grid. The magnitude of the dip is influenced by the percentage load sharing bet ween the generators and microinverter (if connected). Prompt manual voltage correction is necessary to stabilize the Microgrid

e. Immediately increase the generator frequency to 60Hz (1800RPM) at either generator. This action is recommended to be performed by the assigned station watcher.

f. Increase the generator terminal voltage to 120V L-N.

g. Finetuning the generator output power and terminal voltage to ensure equal load sharing.

Expected annunciator status:

- MA-06 “ISLANDED MODE”

8.7 Grid-tied Mode Transfer

NOTE: The grid-tied mode of operation is necessary when one of the generators becomes unavailable or when it is desired by the operator to reconnect to the building grid for power, voltage, and frequency support. The grid-tied mode transfer shall be only conducted when the Microgrid is in islanding mode.

8.7.1 Preparation

a. Ensure the generator frequency is at 60Hz and stable

b. Ensure the generator terminal is from 120V – 125V L-N and stable

8.7.2 Mode Transfer

NOTE: Do not attempt to close circuit breaker CB-U before opening circuit breaker CB1. The building grid and the Microgrid are not synchronized. Such closure will inadvertently trip the Microgrid.

NOTE: CB1 is controlled by SEL-421 automation control with auto synchronism enabled. The synchronization process may take up to 30 seconds depending the angle mismatch between the two grids.

At bench 6:

a. Open circuit breaker CB1.

b. Verify circuit breaker CB1 has been opened (green LED light illuminates).

c. Close circuit breaker CB-U.

d. Monitor circuit breaker CB1 status.

e. Verify circuit breaker CB1 has been closed (red LED light illuminates)

NOTE: The voltage will spike upon synchronizing with the building grid due to the presence of additional VAR support.

f. Increase the generator terminal voltage to 120V L-N.

g. Finetuning the generator output power and terminal voltage to ensure equal load sharing.

Expected annunciator status:
- MA-06 “GRID-TIED”

9. DE-ENERGIZATION

NOTE: The de-energization process will trigger multiple generator and grid alarms. This is expected as the monitored parameters are coming offline. The annunciator panels can be disregarded.

9.1 Microgrid Shutdown

9.1.1 Generator Isolation

At the generator cart #1:

a. Press the “Stop” button on the DC starter #1 to turn off generator #1.

b. Turn OFF the DC starter switch.

c. Turn the potentiometer counterclockwise all the way to completely isolate field current from the generator

At the generator cart #2:

d. Press the “Stop” button on the DC starter #2 to turn off generator #2.

e. Turn OFF the DC starter switch.

f. Turn the potentiometer counterclockwise all the way to completely isolate field current from the generator.

9.1.2 Microinverter Isolation

At the solar panel cart #1:

a. Turn OFF the DC disconnect switch beneath the solar panels.

b. Disconnect the MC4 connectors between the solar panels and the DC transmission cables.

c. Turn the solar panels away from the sun if panels are not expected to be stored in Room 101 within 30 minutes.

At the microinverter cart #1:

d. Open circuit breaker CB-SOLAR.

e. Turn OFF the disconnect switch.

f. Disconnect the MC4 connectors between the DC transmission cables and the microinverter.

9.1.3 Microgrid Isolation

a. Open the circuit breaker CB-U

b. Verify no voltage and current reading on bench 6 Yokogawa.

c. Open circuit breaker CB1

d. Verify circuit breaker CB1 has been opened (Green LED light illuminating)

e. Open the remaining circuit breakers

i. Turn OFF the GHI terminal switches (125V DC power supply) on bench 5 and bench 6. Verify all circuit breakers' green LEDs are off.

9.1.4 Power distribution isolation

<u>At the main distribution panel:</u>

> **<u>NOTE:</u>** All disconnections shall be performed from source-to-load sequence

a. Unplug heavy-duty cables connecting the 120/208VAC source (light green slots) to the ABC slots #6.

b. Turn OFF the two 120V.DC circuit breakers (downward) and press the red motor button at the 125/250V.DC M-G SET panel to de-energize the main DC source.

c. Observe the DC meter gradually rotates to the 0 V position.

d. Turn OFF the GHI #5, GHI #6, and ABC #6 circuit breakers.

<u>At the power lab control panel:</u>

e. Switch OFF (downward) switch #5 and switch #6.

f. Verify that orange lights #5 and #6 diminish.

g. Press the red “Emergency” button on the panel.

h. Verify the green light diminishes

9.1.5 Relay/Speedometer Setup

<u>Below the generator #2 cart:</u>

e. Turn OFF the power strip.

f. Verify the left most SEL-700G relay and Magtrol speedometer power down.

<u>Below the generator #1 cart:</u>

g. Turn OFF the power strip.

h. Verify the SEL-700G, SEL-751, SEL-735s, and Magtrol speedometer power down.

9.2 Housekeeping

9.2.1 Lab Room 101

a. Retract the solar panels.

b. Ensure both doors are fully opened.

c. Move the solar panel cart to Room 102.

d. Keep the cart clear of the main aisle.

e. Store the traffic cones and the 12 V battery under the solar panel cart.

f. Close Room 102.

9.2.2 Lab Room 102

a. Ensure the DC transmission cable is stored underneath bench 6.

b. Verify no tripping hazards nearby the benches 5 and 6.

c. Verify all AC and DC sources at benches 5 and 6 are OFF.

d. Verify the green light at the power lab control panel is OFF

e. Turn OFF the LCD TV for the annunciator panel

f. Turn OFF all room lights before leaving room 102.

10. LOAD SHEDDING SCHEME TEST

NOTE: Load shedding is designed to shed load upon grid frequency reduction. The primary reason for frequency instability is power generation deficiency that typically caused by the solar panel power reduction. This section provides instruction to test the load shedding scheme.

NOTE: Prerequisites for Section 10 are the completion of Step 8.5 and Step 8.6.2

10.1 Preparation

10.1.1 Prerequisite Check

a. Ensure Step 8.5 has been completed.

b. Verify Step 8.6.2 has been completed

c. Tilt the solar panel to obtain maximum output power.

d. Verify the microinverter output power (> 100 W) and stable at the power meter panel to ensure a successful test.

Expected annunciator status:
- MA-06 “GRID-TIED”
- MD-06 “INVERTER SYNCHED”
- MA-04 “INVERTER POWER NORMAL”

10.1.2 Parameter Tuning

At the solar panel cart:

a. Adjust the DC knob (generator power) to obtain 1799 to 1801 RPM.

b. Simultaneously adjust the generator terminal voltage to ensure 120 V L-N.

c. Optionally finetune the generator output power to ensure appropriate real power and reactive contribution according to test criteria.

d. Record initial condition parameters such as grid voltage, frequency, generator output power, and microinverter output power as necessary.

10.2 Load Shedding Test

NOTE: Step 10.2.1 and Step 10.2.2 shall be performed simultaneously. This can be achieved by assigning one person (Observer #1) at the solar panel cart and one person at lab bench #5 (Observer #2). Cellphone communication shall be established to ensure coordination and safety.

10.2.1 Solar Panel Power Reduction

At the solar panel cart:

a. Ensure the solar tracker controller is set to manual by pressing the “SET” button on the remote control.

b. Use the remote control to raise the panel angle away from the optimal position.

c. Briefly press the “W →” button to raise the angle such that the solar panels rotate no more than 2 inches of angular distance.

d. Each pressing shall be communicated with Observer #2.

e. Repeat step 10.2.1c/d until further notice by Observer #2.

10.2.2 Microgrid Observation

At lab bench 5:

a. Observe grid voltage and frequency (or speed in RPM) at the meter panel.

b. Maintain communication with Observer #1.

c. Provide grid parameters information as necessary to Observer #1.

d. Direct Observer #1 to tilt the solar panels by no more than 1 inch of angular distance as the grid frequency/speed approaches 59.87 Hz or ~1796 RPM.

   Expected annunciator status:
   - MC-07 “ISLANDING ABORT”
   - MD-07 “INSUFFICIENT POWER/FREQ UNSTABLE”
   - MA-05 “STATIC LOAD CONNECTED”

e. Prepare to take necessary data

f. Direct Observer #1 to cease all activities at solar panels cart once load shedding occurs. Grid generally behaves as follows:

   - Generator speed increases to 1805 RPM to 1810 RPM.
   - Generator voltage increases to 120 – 125 V L-N.
   - Audible breaker closure from CB-SHED

   Expected annunciator status:
   - MA-05 “LOAD SHED”

11. REMARKS

Document any findings or abnormalities that might affect the safe operation of the Microgrid. Remark section can be used as notes.

REMARK:____

ATTACHMENT 1 – Room 102 Layout

This attachment contains the floor layout of laboratory room 102.

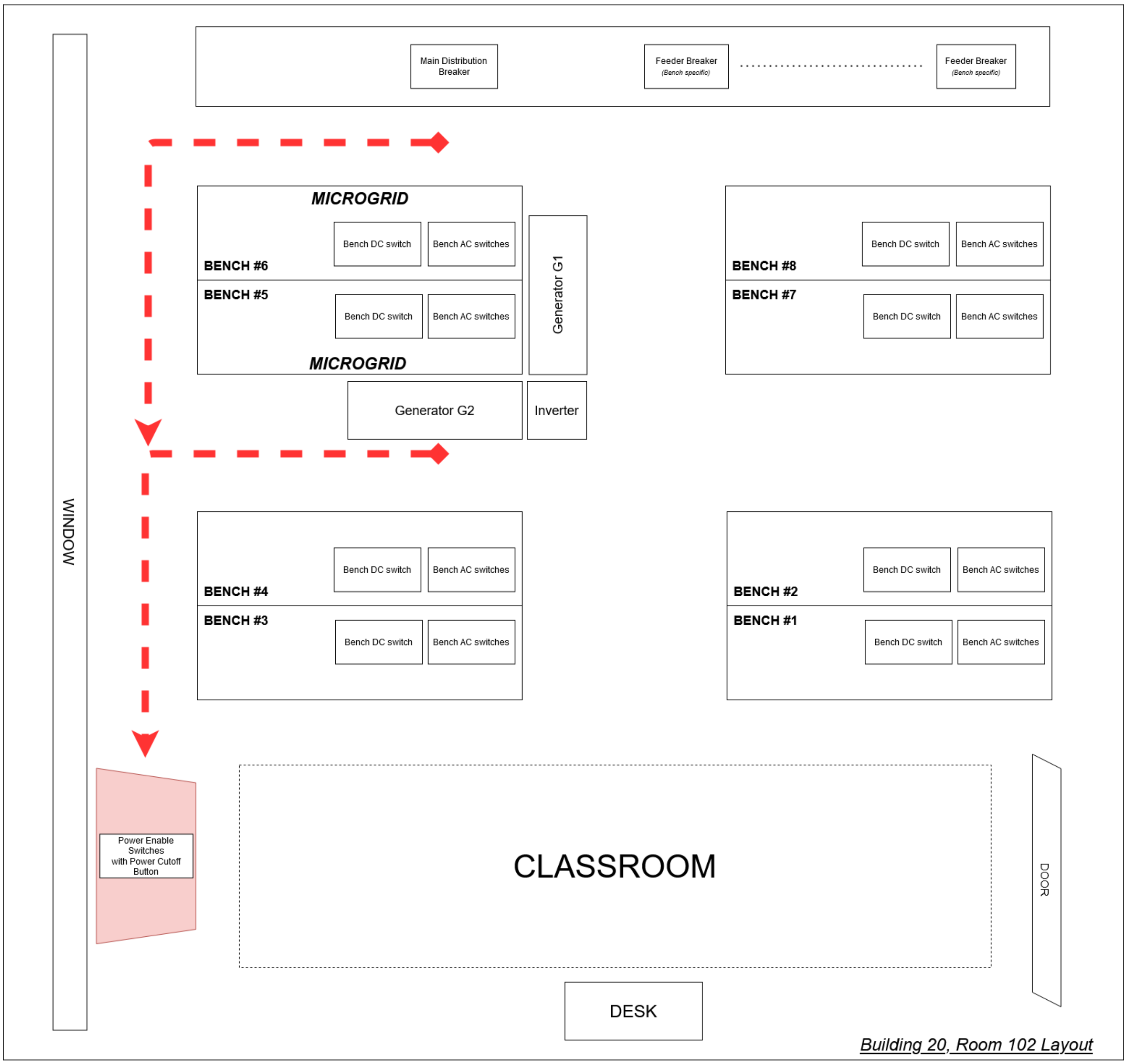


Figure 1. Room 102 Layout

ATTACHMENT 2 – Pictorial References

This attachment contains pictorial references of Microgrid's components.

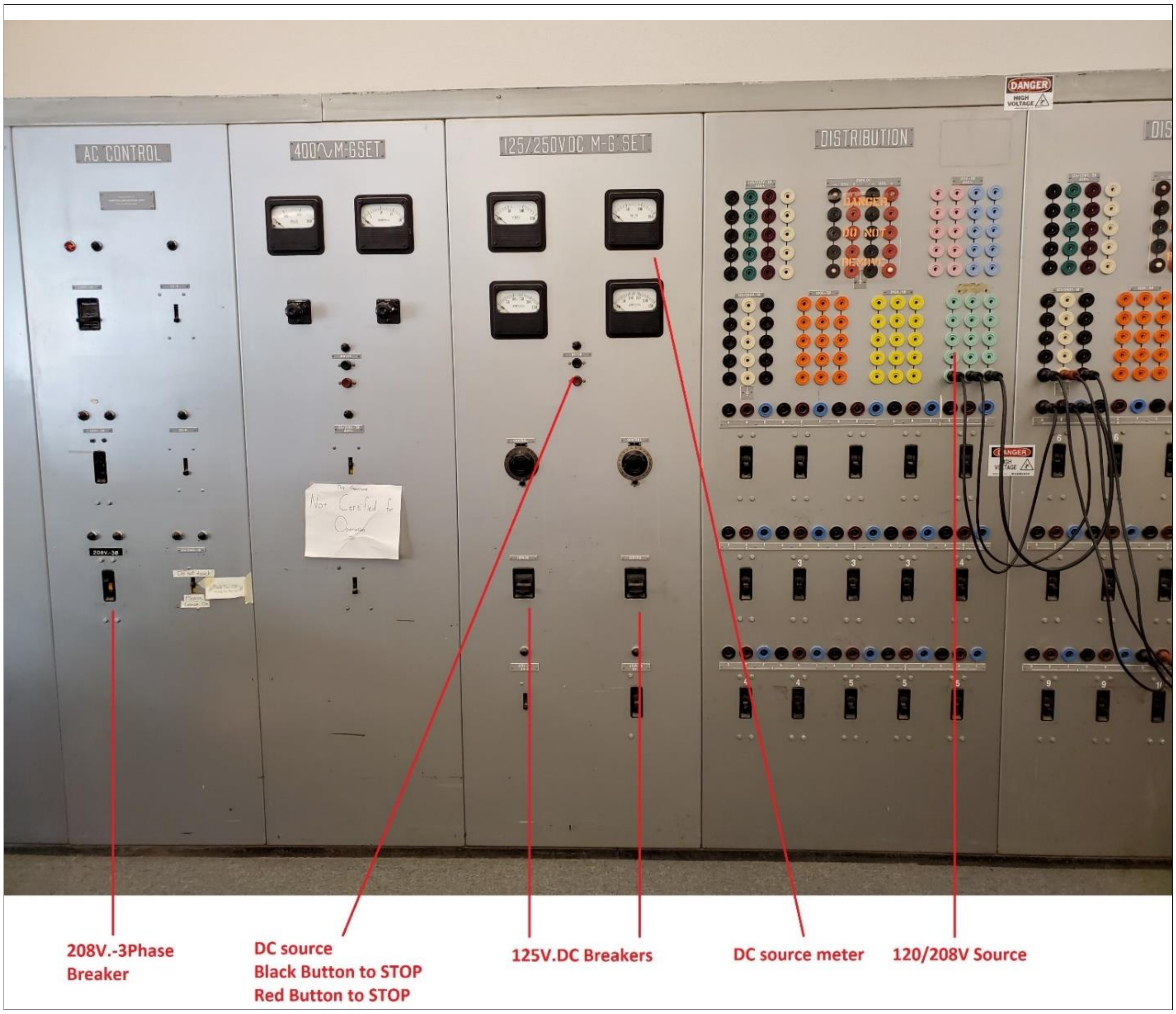


Figure 1. Main Distribution Panel (1)

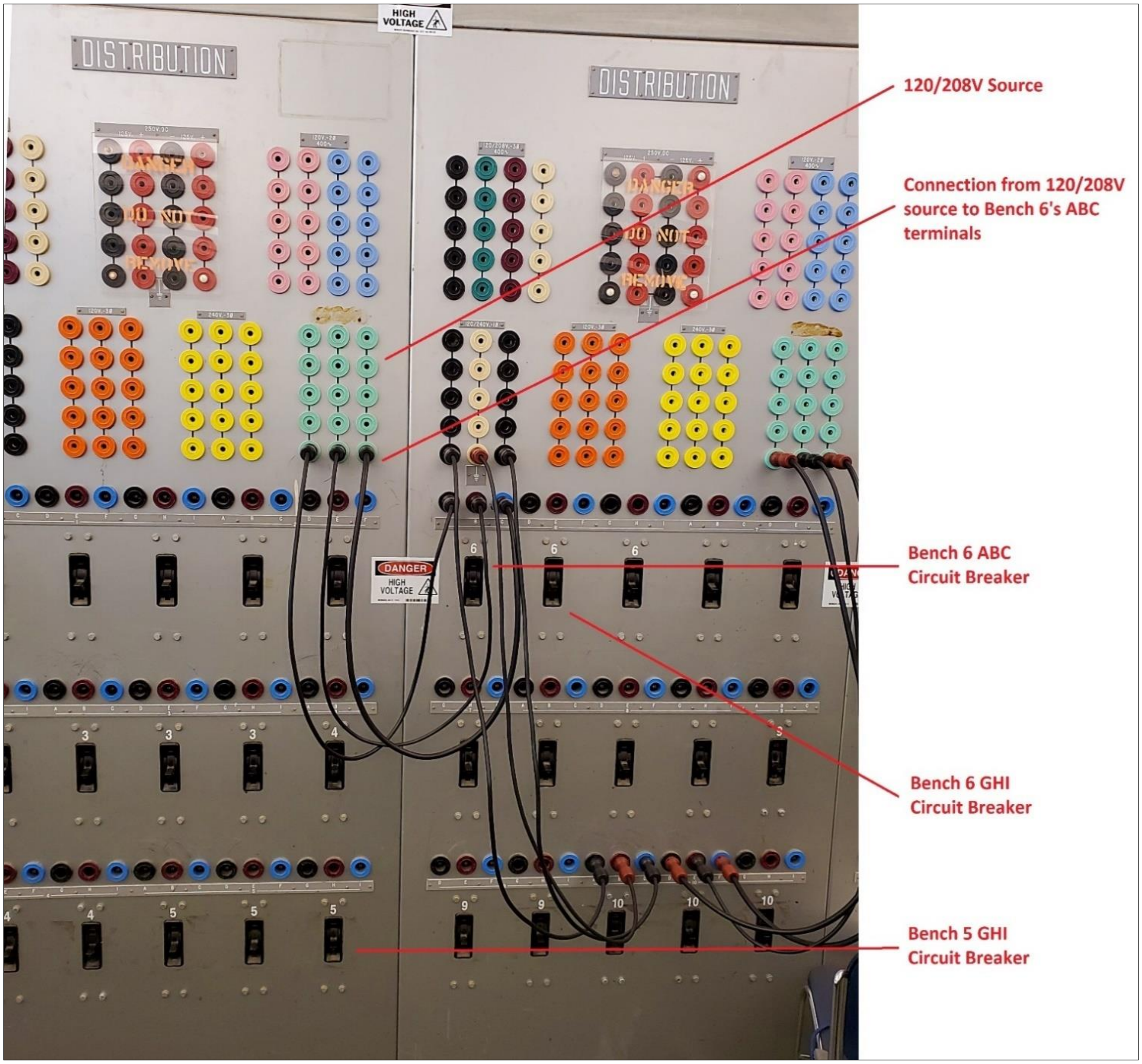


Figure 2. Main Distribution Panel (2)

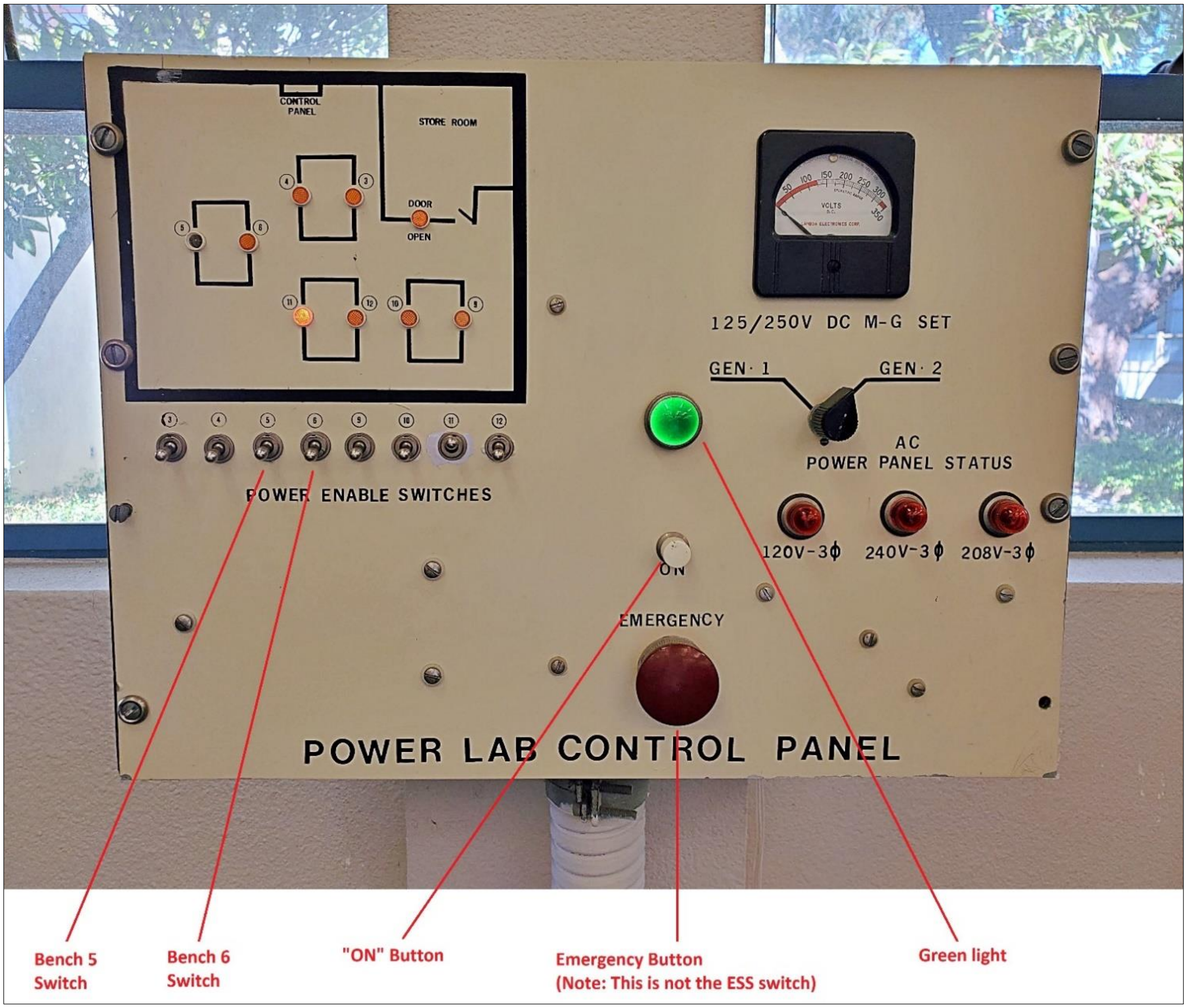


Figure 3. Power Lab Control Panel

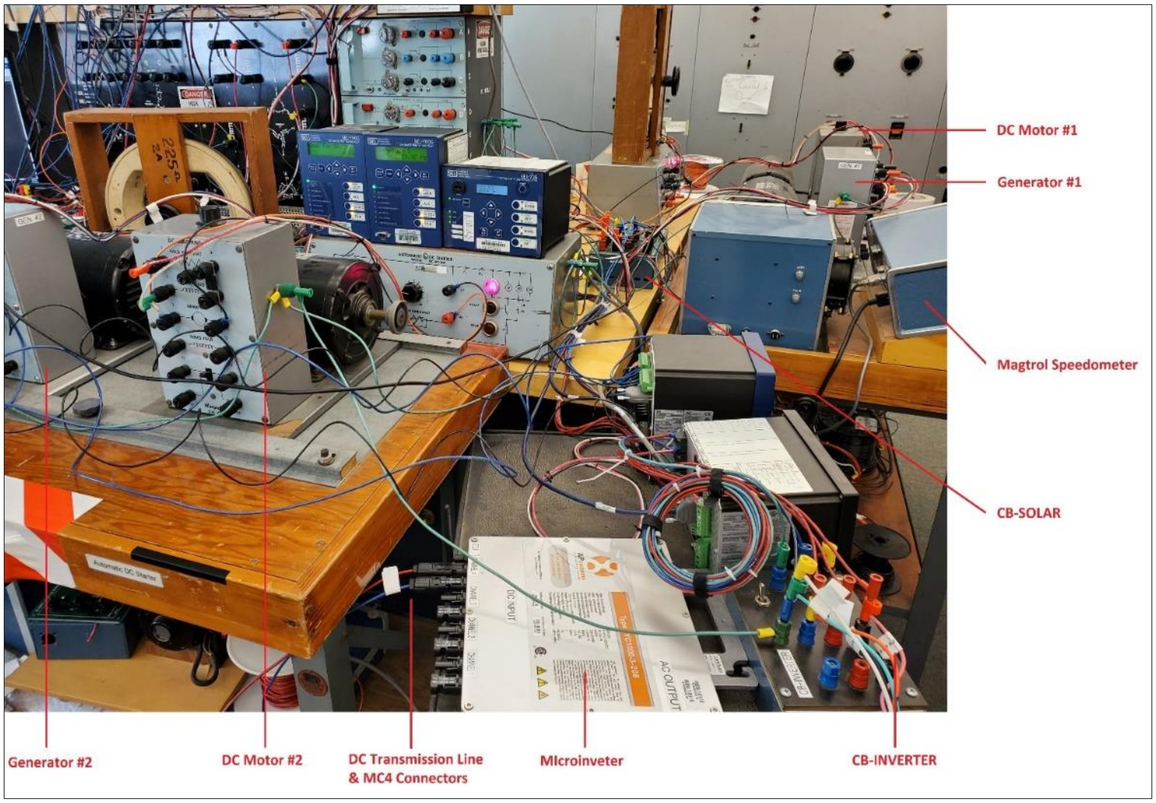


Figure 4. Power Generation Setup

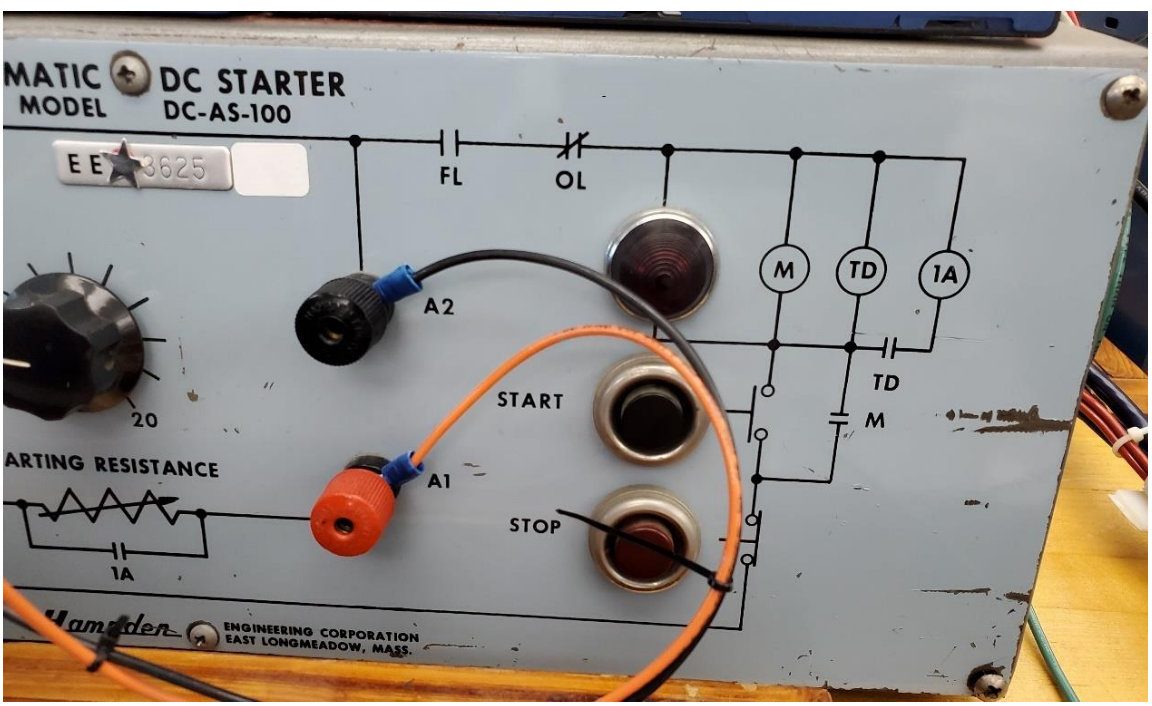


Figure 5. DC Motor Starter Start/Stop Buttons

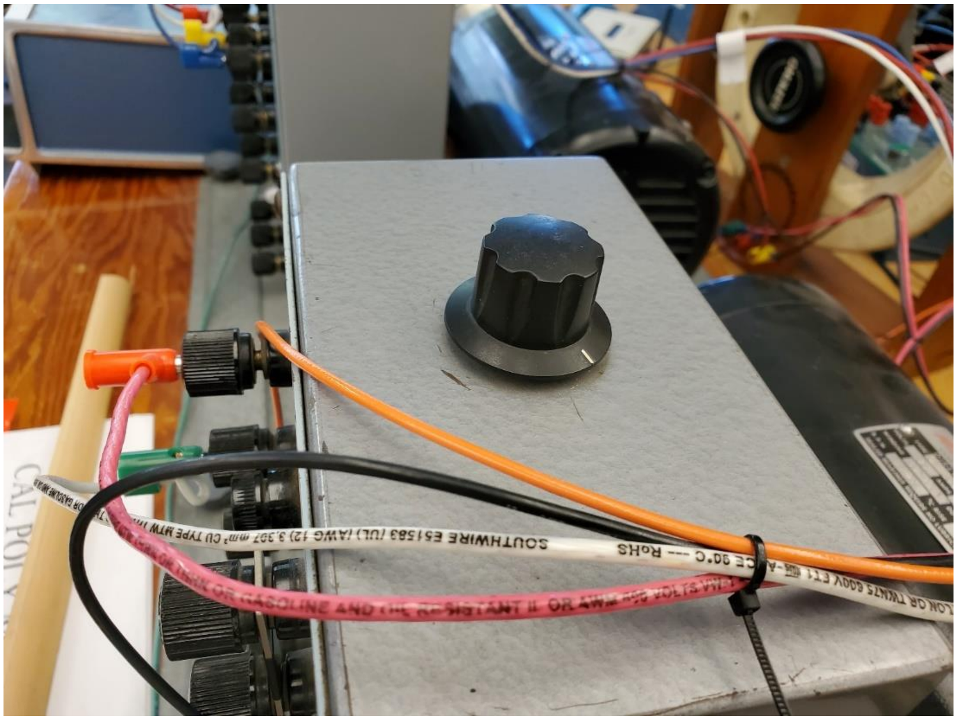


Figure 6. DC Motor Speed Control Knob

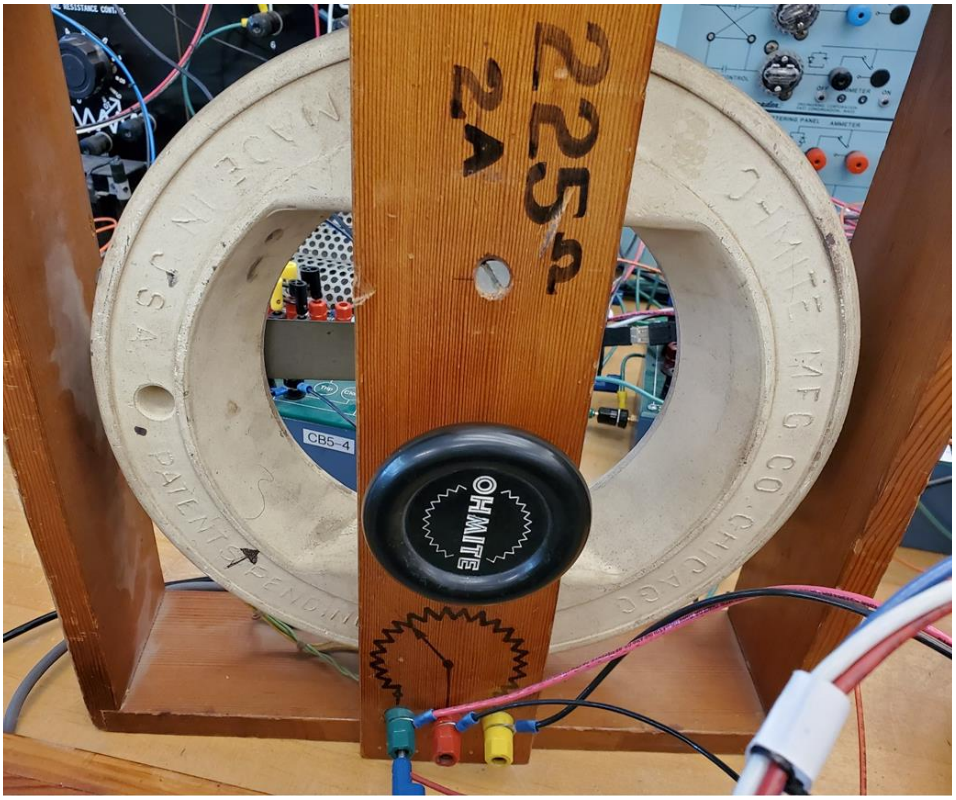


Figure 7. Generator Field Current Potentiometer

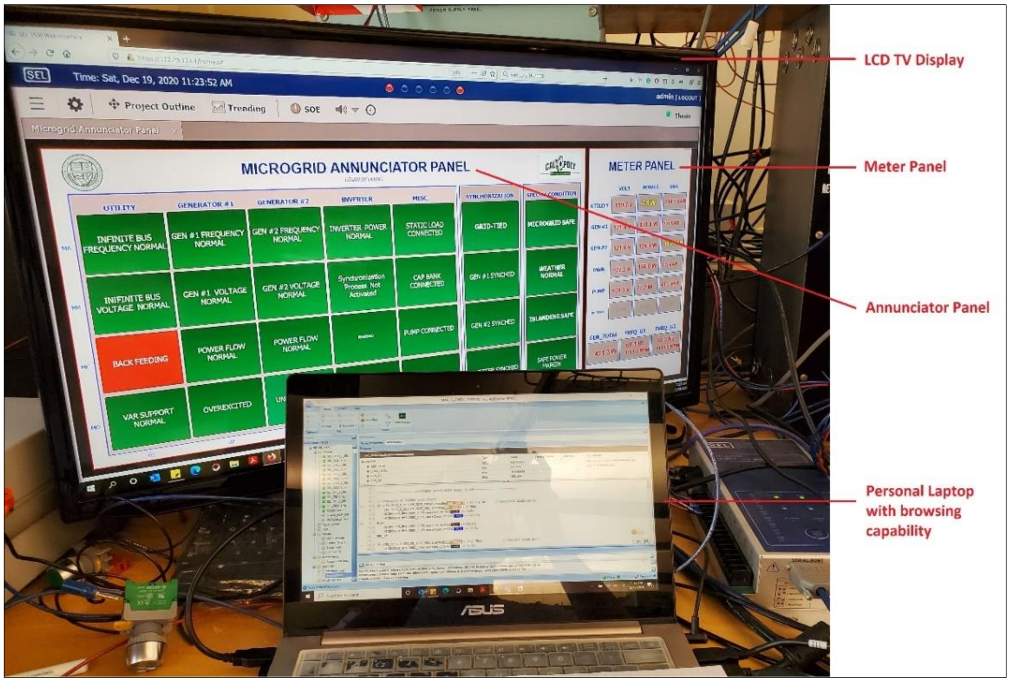


Figure 8. Annunciator Panel Station with a Personal Laptop

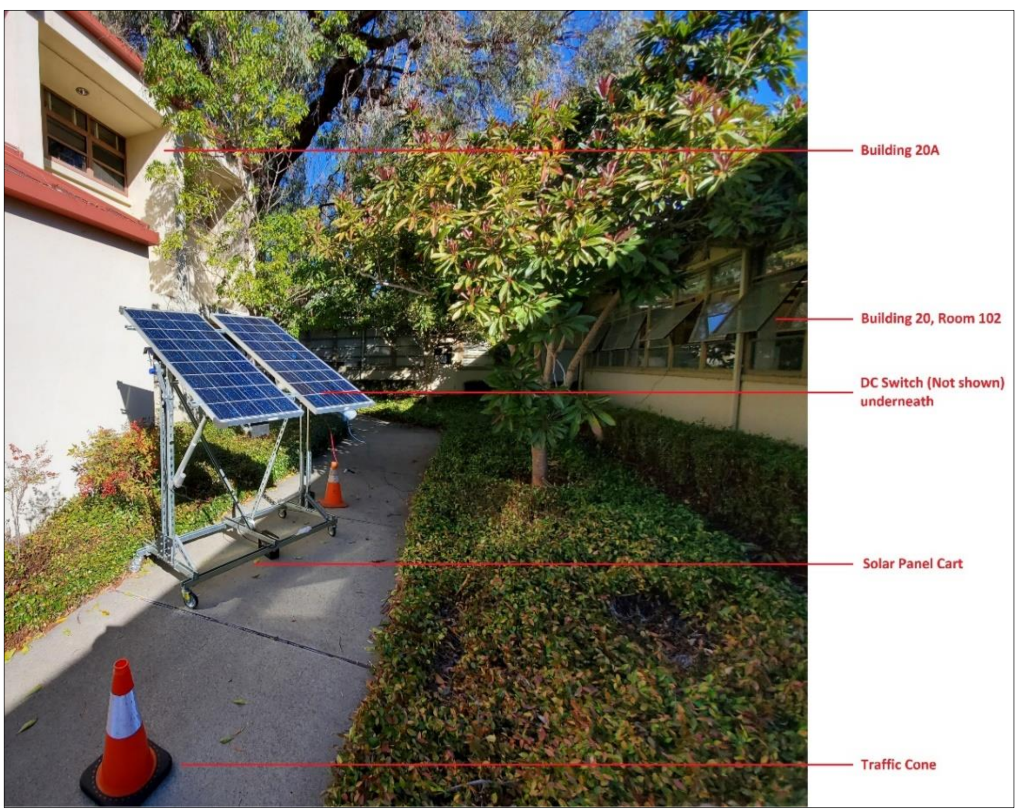


Figure 9. Solar Panel Cart Setup (1)

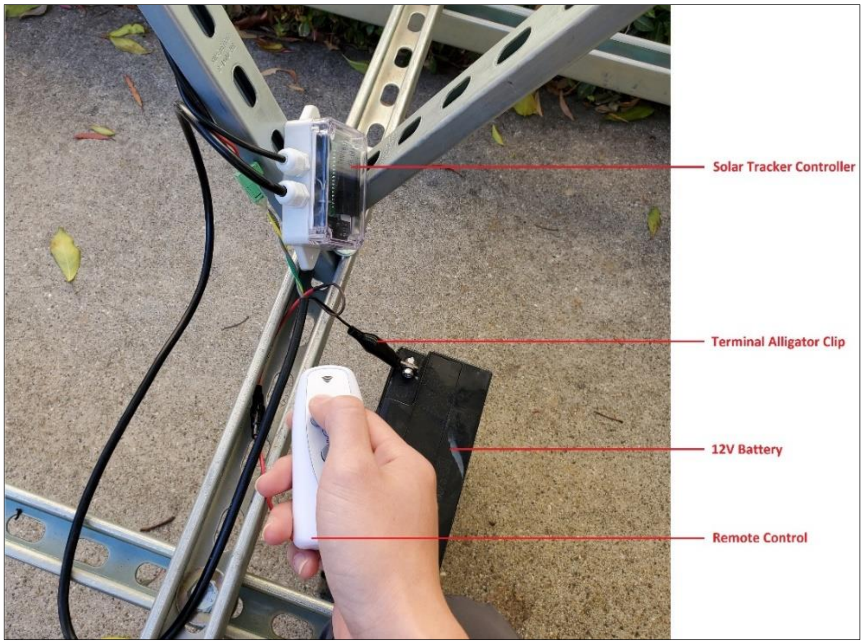


Figure 10. Solar Panel Cart Setup (2)

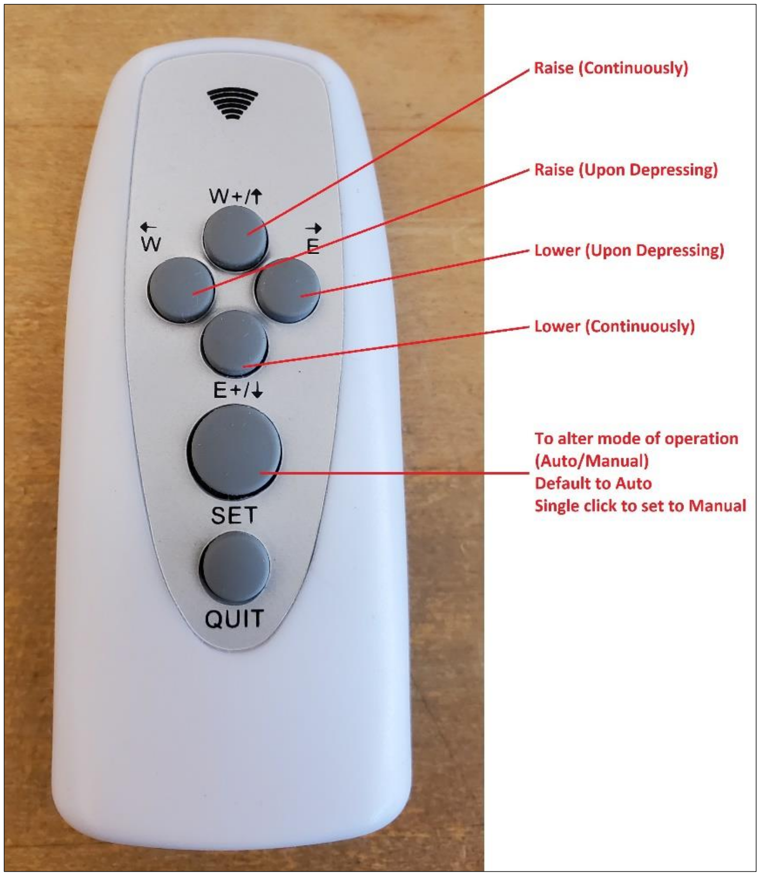


Figure 11. Solar Tracker Remote Control

ATTACHMENT 3 – Placekeeping Demo

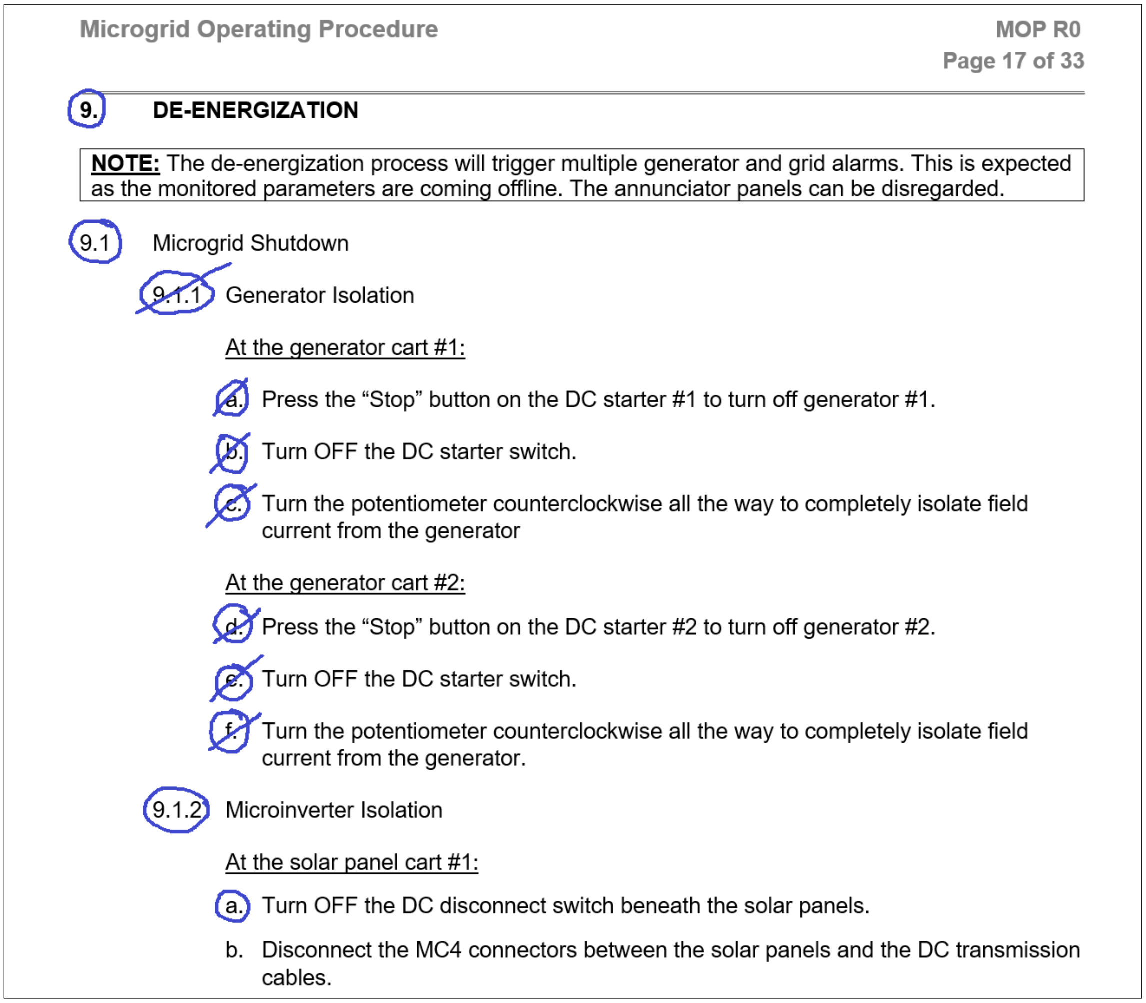
This attachment provides an instruction to conduct a proper placekeeping.

The Microgrid Operating Procedure is broken down into various sections and subsections. For example, Section 8 “INSTRUCTIONS” consists of many subsections such as Section 8.1 “Preparation” and Section 8.2 “Start-up”. Each of these subsections have their own subsections which contains instructional steps.

Once entered any section, subsection or step, the corresponding numerical designation must be circled. Once each section, subsection, or step is fully completed, the circle must be forward slashed. If step has been mistakenly marked as completed, the circle shall be crossed, and a new circle shall be drawn beside. If a step or subsection cannot be used due, the corresponding numerical designation shall be forward slashed and with an “N/A” mark.

The following examples demonstrate a proper placekeeping technique.

Example 1: The operator just completed Step 9.1.1f as a part of Subsection 9.1.1, Subsection 9.1, of Section 9. He/she is performing Step 9.1.2a and Subsection 9.1.2. The operator circle slashed up to the last completed step, Step 9.1.1f and only circled Step 9.1.2a.



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9. **DE-ENERGIZATION**

NOTE: The de-energization process will trigger multiple generator and grid alarms. This is expected as the monitored parameters are coming offline. The annunciator panels can be disregarded.

9.1 Microgrid Shutdown

9.1.1 Generator Isolation

At the generator cart #1:

a. Press the “Stop” button on the DC starter #1 to turn off generator #1.

b. Turn OFF the DC starter switch.

c. Turn the potentiometer counterclockwise all the way to completely isolate field current from the generator

At the generator cart #2:

d. Press the “Stop” button on the DC starter #2 to turn off generator #2.

e. Turn OFF the DC starter switch.

f. Turn the potentiometer counterclockwise all the way to completely isolate field current from the generator.

9.1.2 Microinverter Isolation

At the solar panel cart #1:

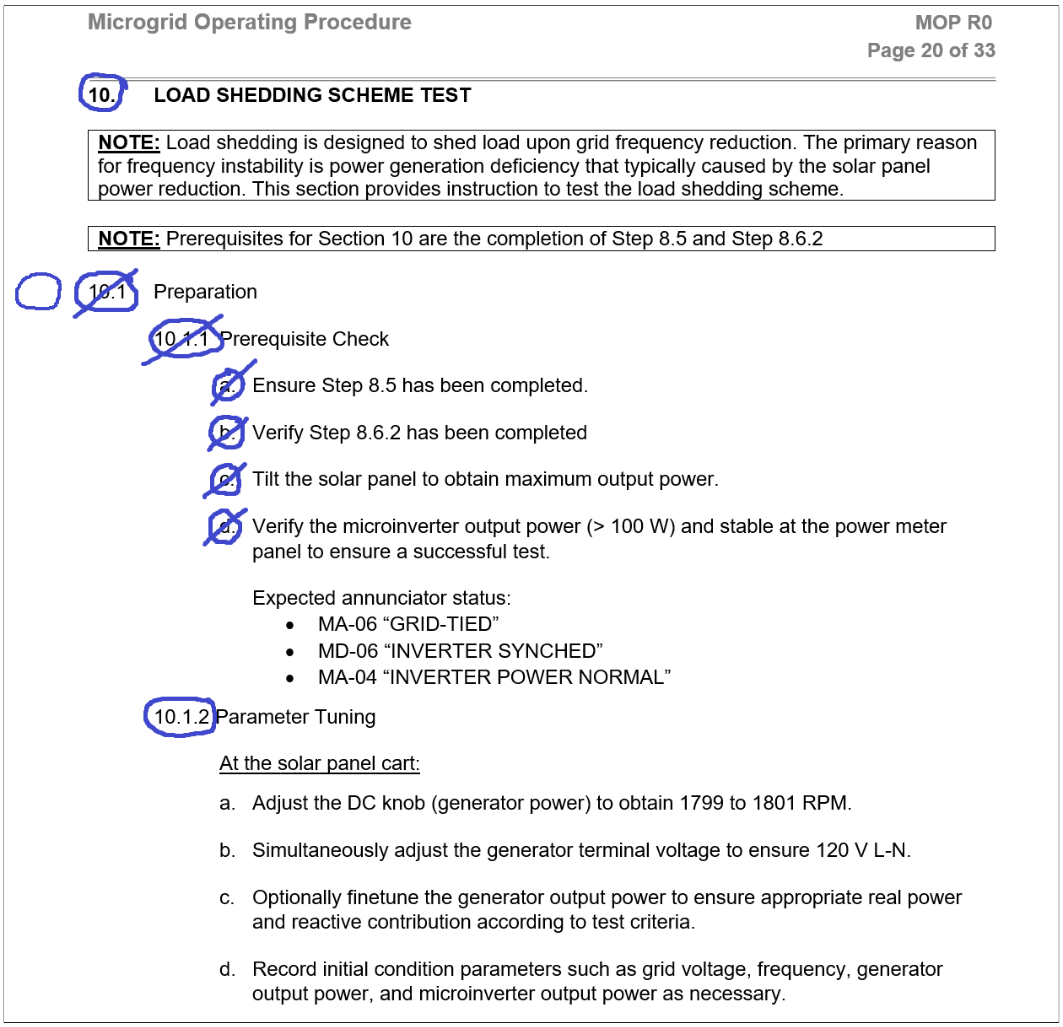
a. Turn OFF the DC disconnect switch beneath the solar panels.

b. Disconnect the MC4 connectors between the solar panels and the DC transmission cables.

Figure 1. Example 1 (Placekeeping Demo)

Example 2: The operator just completed Subsection 10.1.1 as a part of Subsection 10.1 and is entering Subsection 10.1.2. However, the operator mistakenly circled and forward slashed Subsection 10.1 which has not been completed due to the incompletion of Subsection 10.1.2. The operator fixes the mistake by crossing the existing circle and marking a new circle on the left.

This process can be used when redoing an earlier step that have already been circle slashed.



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10. LOAD SHEDDING SCHEME TEST

NOTE: Load shedding is designed to shed load upon grid frequency reduction. The primary reason for frequency instability is power generation deficiency that typically caused by the solar panel power reduction. This section provides instruction to test the load shedding scheme.

NOTE: Prerequisites for Section 10 are the completion of Step 8.5 and Step 8.6.2

10.1 Preparation

10.1.1 Prerequisite Check

a. Ensure Step 8.5 has been completed.

b. Verify Step 8.6.2 has been completed

c. Tilt the solar panel to obtain maximum output power.

d. Verify the microinverter output power (> 100 W) and stable at the power meter panel to ensure a successful test.

Expected annunciator status:
- MA-06 “GRID-TIED”
- MD-06 “INVERTER SYNCHED”
- MA-04 “INVERTER POWER NORMAL”

10.1.2 Parameter Tuning

At the solar panel cart:

a. Adjust the DC knob (generator power) to obtain 1799 to 1801 RPM.

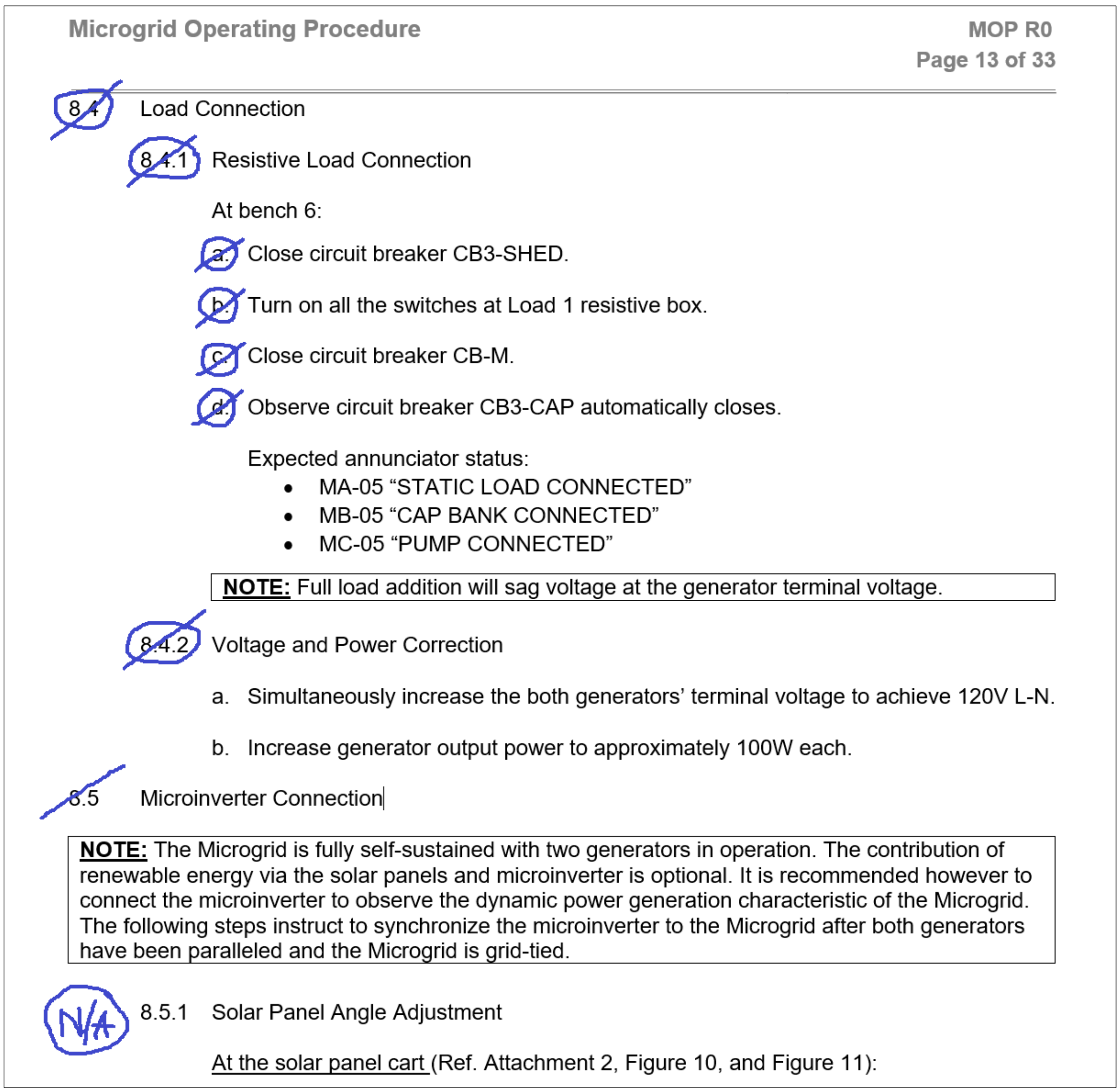
b. Simultaneously adjust the generator terminal voltage to ensure 120 V L-N.

c. Optionally finetune the generator output power to ensure appropriate real power and reactive contribution according to test criteria.

d. Record initial condition parameters such as grid voltage, frequency, generator output power, and microinverter output power as necessary.

Figure 2. Example 2 (Placekeeping Demo)

Example 3: The operator just completed Subsection 8.4. At this point the walkway between Building 20A and Building 20, Room 102 has been shaded. The operator decided not to connect the solar panels and microinverter to the Microgrid. As a result, Subsection 8.5 will not be used. The operator forward slashed the corresponding numerical designation and wrote “N/A” to clarify.



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~~8.4~~ Load Connection

~~8.4.1~~ Resistive Load Connection

At bench 6:

~~a.~~ Close circuit breaker CB3-SHED.

~~b.~~ Turn on all the switches at Load 1 resistive box.

~~c.~~ Close circuit breaker CB-M.

~~d.~~ Observe circuit breaker CB3-CAP automatically closes.

Expected annunciator status:

- MA-05 “STATIC LOAD CONNECTED”
- MB-05 “CAP BANK CONNECTED”
- MC-05 “PUMP CONNECTED”

NOTE: Full load addition will sag voltage at the generator terminal voltage.

~~8.4.2~~ Voltage and Power Correction

a. Simultaneously increase the both generators’ terminal voltage to achieve 120V L-N.

b. Increase generator output power to approximately 100W each.

~~8.5~~ Microinverter Connection

NOTE: The Microgrid is fully self-sustained with two generators in operation. The contribution of renewable energy via the solar panels and microinverter is optional. It is recommended however to connect the microinverter to observe the dynamic power generation characteristic of the Microgrid. The following steps instruct to synchronize the microinverter to the Microgrid after both generators have been paralleled and the Microgrid is grid-tied.

N/A 8.5.1 Solar Panel Angle Adjustment

At the solar panel cart (Ref. Attachment 2, Figure 10, and Figure 11):

Figure 3. Example 3 (Placekeeping Demo)